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VCE CHEMISTRY

Units 3 & 4



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VCE CHEMISTRY

Units 3 & 4

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PUBLISHED IN AUSTRALIA BY Edrolo
321 Exhibition Street Melbourne VIC 3000, Australia

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National Library of Australia Cataloguing-in-Publication data

TITLE: Edrolo VCE Chemistry Units 3 & 4
CREATOR: Edrolo et al.
ISBN: 978-1-922901-24-8
TARGET AUDIENCE: For secondary school age.
SUBJECTS: Chemistry--Study and teaching (Secondary)--Victoria
Chemistry--Victoria--Textbooks.
Chemistry--Theory, exercises, etc.
OTHER CREATORS/CONTRIBUTORS: Sophie Renshaw

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LAYOUT DESIGN: Sam McCarthy, Christopher Dell and Edrolo
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Features of this book

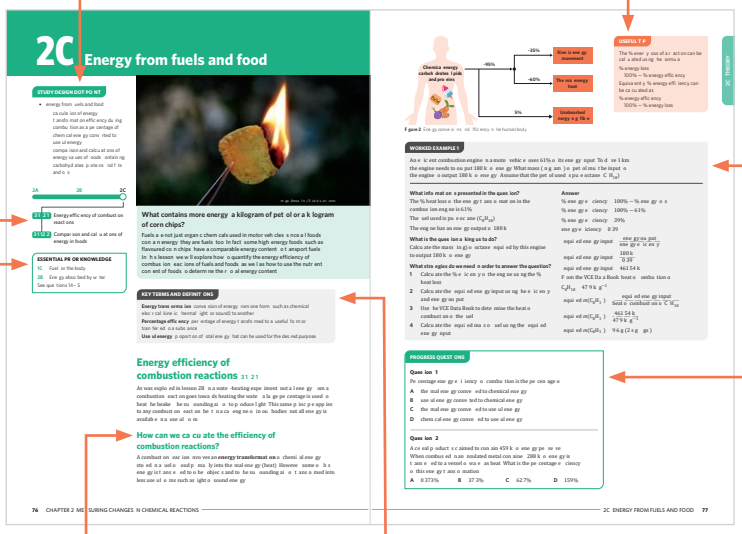
Edrolo's VCE Chemistry Units 3 & 4 textbook has the following features.

Theory

Key knowledge units break down the theory into smaller chunks that help navigate the corresponding theory lesson videos on the Edrolo online platform.

Study design dot points provide explicit links between the content covered in each lesson and the VCAA study design.

Explore boxes include misconceptions, useful tips, strategy, and keen to investigate boxes.



Worked examples apply content to exam-style questions with strategies, full working, and explanations of each step in the process.

Essential prior knowledge questions are designed to break down any misconceptions and highlight prerequisite knowledge from previous lessons that is 'essential' to understanding the lesson's content.

Progress questions test if the students can remember bite-sized chunks of theory and overcome common misconceptions early in their learning journey. They are stepping stones between the content and exam-style questions.

Guiding questions focus and simplify the key knowledge required by the VCAA study design.

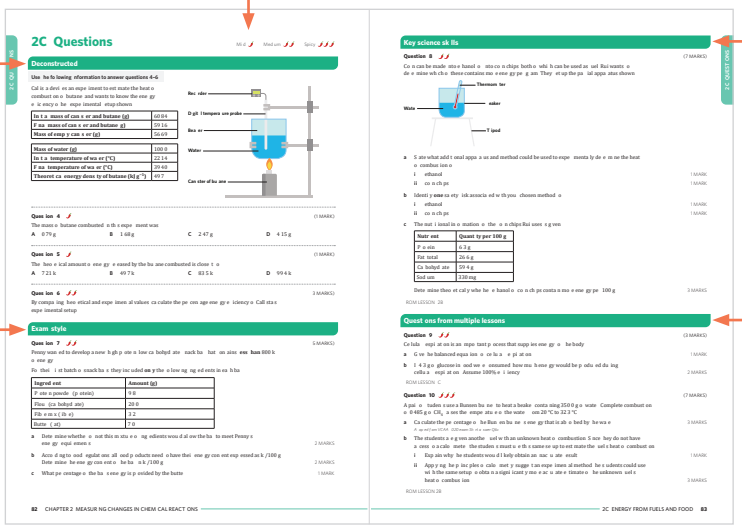
Key terms are defined and highlighted to support learning.

Questions

Spiciness ratings measure the difficulty of the questions, and can be used to differentiate students and teach to their level.

Deconstructed questions provide prompts for students to piece together the steps needed to answer an exam-style question.

Exam-style questions reflect the style of questions presented in end-of-year exams.

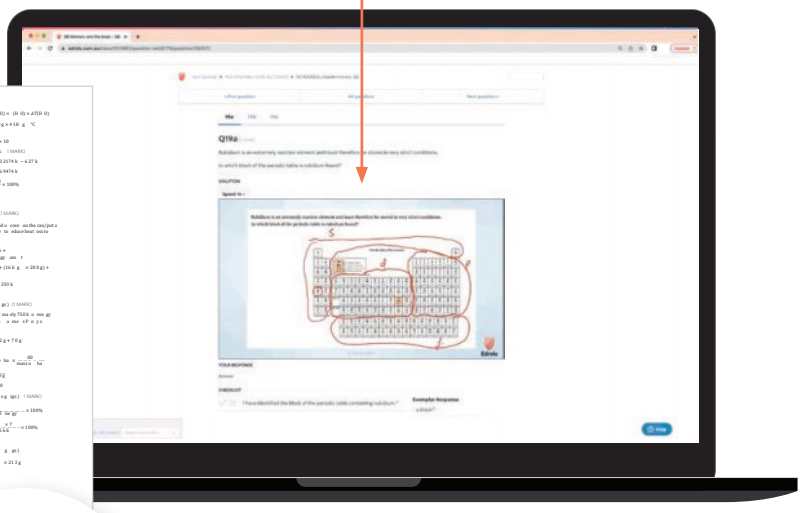


Key science skills questions develop inquiry skills students need for SACs and other assessments.

Questions from multiple lessons combine key knowledge from previous lessons to develop a deeper understanding of concepts.

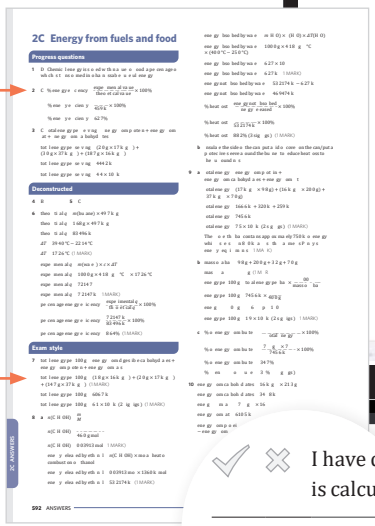
Answers

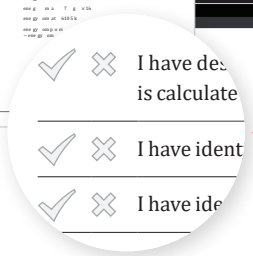
Video solutions provide extra guidance on how to answer questions.



Worded and visual responses include exemplar answers to all questions to show what a full mark response looks like.

Calculation responses show full working along with mark allocations to help students form good habits and to provide more detailed guidance for students.

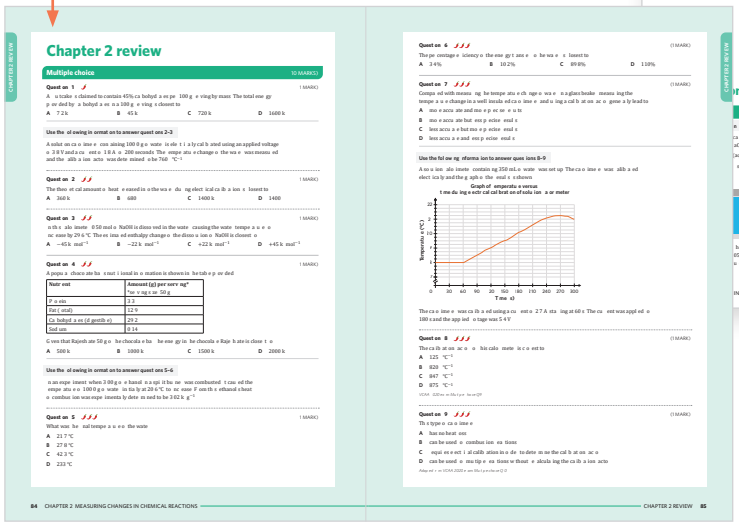


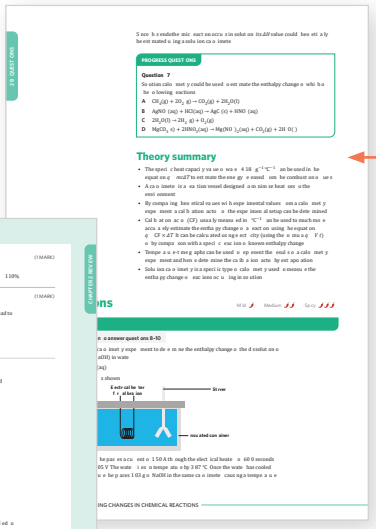


Checklists are provided for all answers (worth more than 1 mark) and they explain the purpose of each part of a full-mark answer to help students develop their scientific communication skills.

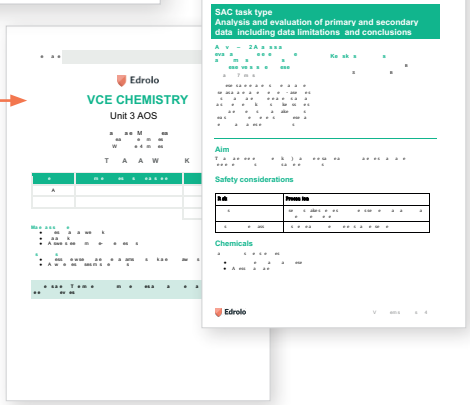
Reviews

Chapter reviews consist of end-of-year exam-style questions that cover content from that chapter or area of study. They are structured into three sections: multiple choice, short answer and key science skills questions.





Theory summaries provide a summary of the key takeaways from each lesson.



Activities are downloadable and editable from your Edrolo account. They can be used as assessments, engagement opportunities, and to enhance content understanding.

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3

UNIT 3

How can design and innovation help to optimise chemical processes?

The global demand for energy and materials is increasing with world population growth. In this unit students investigate the chemical production of energy and materials. They explore how innovation, design and sustainability principles and concepts can be applied to produce energy and materials while minimising possible harmful effects of production on human health and the environment.

Students analyse and compare different fuels as energy sources for society, with reference to the energy transformations and chemical reactions involved, energy efficiencies, environmental impacts and potential applications. They explore food in the context of supplying energy in living systems. The purpose, design and operating principles of galvanic cells, fuel cells, rechargeable cells and electrolytic cells are considered when evaluating their suitability for supplying society's needs for energy and materials. They evaluate chemical processes with reference to factors that influence their reaction rates and extent. They investigate how the rate of a reaction can be controlled so that it occurs at the optimum rate while avoiding unwanted side reactions and by-products. Students conduct practical investigations involving thermochemistry, redox reactions, electrochemical cells, reaction rates and equilibrium systems.

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UNIT 3 AOS 1

What are the current and future options for supplying energy?

In this area of study students focus on analysing and comparing a range of fossil fuels and biofuels as energy sources for society, and carbohydrates, proteins and lipids as fuel sources for the body. They write balanced thermochemical equations for the combustion of various fuels. The amounts of energy and gases produced in combustion reactions are quantified using stoichiometry. They explore how energy can be sustainably produced from chemicals to meet the needs of society while minimising negative impacts on the environment.

The selection of learning contexts should allow students to develop practical techniques to investigate how energy from fuels can be obtained and measured, and to determine the efficiency of different fuels and electrochemical cells as sources of energy. Students develop their skills in the use of scientific equipment and apparatus. They may measure energy released in combustion reactions through quantitative calorimetry experiments and may compare amounts of energy released in different fuels, such as methane, alcohols, waxes and foods.

They design, construct and test galvanic and fuel cells, and account for differences between experimental findings and predictions made by using the electrochemical series. Students may work collaboratively to construct electrochemical half-cells and experiment with different combinations of half-cells to develop their own electrochemical series. Students respond to challenges such as designing an electrochemical cell that generates the most energy under laboratory conditions using a limited range of supplied chemicals and materials.

Outcome 1

On completion of this unit the student should be able to compare fuels quantitatively with reference to combustion products and energy outputs, apply knowledge of the electrochemical series to design, construct and test primary cells and fuel cells, and evaluate the sustainability of electrochemical cells in producing energy for society.

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1

CHAPTER 1
Carbon-based fuels

LESSONS

1A Fossil fuels

1B Biofuels

1C Fuel for the body

1D Enthalpy changes and combustion reactions

Chapter 1 review

KEY KNOWLEDGE

- the definition of a fuel, including the distinction between fossil fuels (coal, natural gas, petrol) and biofuels (biogas, bioethanol, biodiesel) with reference to their renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)
- fuel sources for the body measured in kJ g^{-1}: carbohydrates, proteins and lipids (fats and oils)
- photosynthesis as the process that converts light energy into chemical energy and as a source of glucose and oxygen for respiration in living things: $6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$
- oxidation of glucose as the primary carbohydrate energy source, including the balanced equation for cellular respiration: $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$
- production of bioethanol by the fermentation of glucose and subsequent distillation to produce a more sustainable transport fuel: $C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$
- comparison of exothermic and endothermic reactions, with reference to bond making and bond breaking, including enthalpy changes (ΔH) measured in kJ, molar enthalpy changes measured in kJ mol^{-1} and enthalpy changes for mixtures measured in kJ g^{-1}, and their representations in energy profile diagrams
- determination of limiting reactants or reagents in chemical reactions
- combustion (complete and incomplete) reactions of fuels as exothermic reactions: the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of organic molecules using experimental data and data tables

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1A Fossil fuels

STUDY DESIGN DOT POINT

- the definition of a fuel, including the distinction between fossil fuels (coal, natural gas, petrol) and biofuels (biogas, bioethanol, biodiesel) with reference to their renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)

1A 1B 1C 1D

3.1.1.1 Definition of fuels

3.1.1.2 Non-renewability of fossil fuels

ESSENTIAL PRIOR KNOWLEDGE

- Molecules
- Hydrocarbons
- Combustion

See questions 1–3.

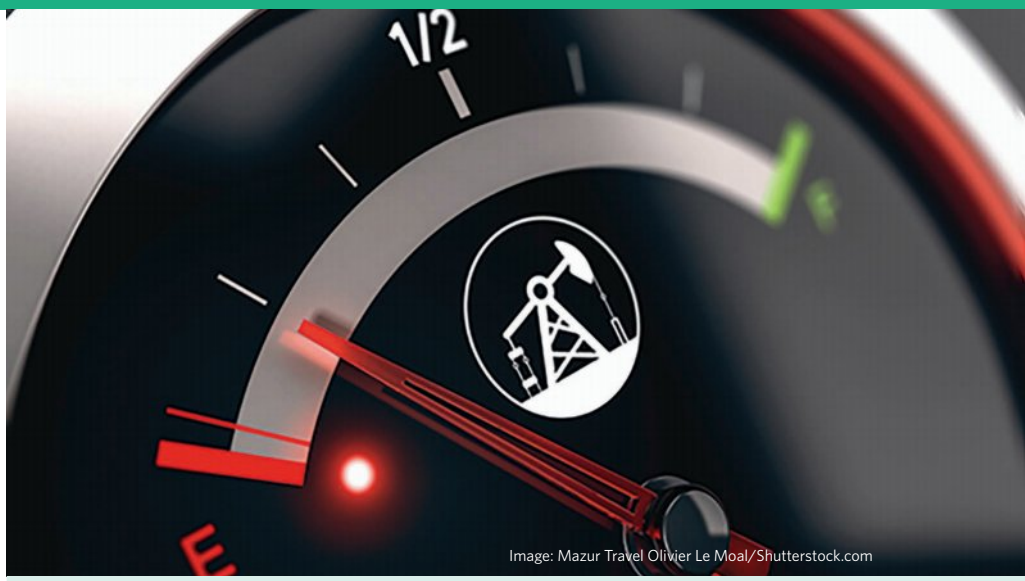


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For how many more years can we continue using coal and natural gas?

Although **fossil fuels** remain, in most cases, the cheapest sources of energy, the over-reliance on them as our primary energy resource is no longer **sustainable**. In this lesson, we will learn about some of the different types of fossil fuels and why they are considered non-renewable.

KEY TERMS AND DEFINITIONS

Chemical decomposition process in which larger chemical species are broken into simpler molecules

Coal combustible fossil fuel formed by the partial decay of plant and animal matter

Coal seam gas natural gas sourced from coal deposits

Crude oil viscous black mixture of hydrocarbons

Enhanced greenhouse effect process of the warming of the Earth's lower atmosphere due to the increased concentration of gases like carbon dioxide, water vapour and methane in the air

Fossil fuel natural fuel that is formed under the Earth's crust from the decomposition of plant and/or animal remains over millions of years

Fuel substance that is used (usually combusted) to produce energy

Natural gas fossil fuel consisting of small hydrocarbon molecules

Non-renewable resource resource that cannot be replaced by natural processes within a relatively short period of time

Petrol liquid hydrocarbon fossil fuel purified from crude oil

Petroleum complex mixture of hydrocarbons (often called crude oil) found under Earth's crust

Sustainable can be produced at a rate that is greater than or equal to the rate of consumption without compromising future generations

Definition of fuels 3.1.1.1

Fossil fuels are substances that have been formed by the **chemical decomposition** of organic matter over millions of years, and contain chemical energy that can be converted into useful electrical, heat, and kinetic energy.

What is a fuel?

Fuels are incredibly useful substances that contain chemical energy, which can be readily released through combustion reactions (i.e burning) to produce heat energy. Energy is measured in the SI unit joule (J). A single joule is a relatively small amount of energy; table 1 shows some more common units of energy used in VCE chemistry.

Table 1 List of common units of energy

Name	Unit of energy
Kilojoules	$1\ \text{kJ} = 10^3\ \text{J}$
Megajoules	$1\ \text{MJ} = 10^6\ \text{J}$
Gigajoules	$1\ \text{GJ} = 10^9\ \text{J}$
Terajoules	$1\ \text{TJ} = 10^{12}\ \text{J}$

USEFUL TIP

Mathematical prefixes (e.g. kilo) can be found in the VCE Data Book.

A fossil fuel is a specific type of fuel that is named due to the way it is formed from the remains of plants and/or animals. They can be extracted by various methods, as shown in figure 1 (for information only, as the origin and methods of extraction are outside the scope of the study design). Fossil fuels are currently the world's primary energy source – without them, we wouldn't be able to provide most of the energy required for fulfilling human needs.

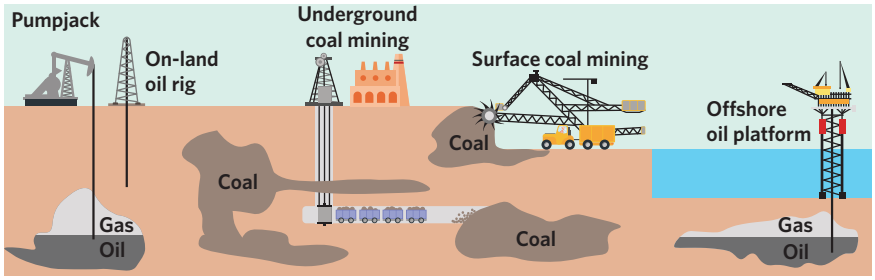


Figure 1 Overview of different extraction methods of coal and gas

Common fossil fuels include **coal**, **petrol** and **coal seam gas**, each of which are derived from the decomposition of plants and/or marine creatures and/or animals over millions of years. Coal seam gas is a type of **natural gas** composed mainly of methane (figure 2). All of these mentioned fossil fuels have a high carbon content, making them excellent substances to burn. The amount of energy that is produced from the combustion reactions of fuels is dependent on the type of fuel being burned.



Image: Mazur Travel/Shutterstock.com

Figure 2 Coal seam gas has been escaping through the bedrock of a mountain in Turkey, called the 'Flames of Chimaera', for over 2500 years.



Image: Kirill Gorshkov/Shutterstock.com

Figure 3 Crude oil is a very viscous (thick) and toxic mixture composed of around sixty species of organic compounds.

MISCONCEPTION

'Natural gas only contains methane gas.'

Natural gas is a mixture of gases including methane (~90%), ethane, propane, butane, carbon dioxide and nitrogen. The exact composition varies depending on where it is extracted from.

Petroleum, also known as **crude oil**, is a black and viscous mixture of hydrocarbons (figure 3) that needs to be separated in a process known as fractional distillation (figure 4). Fractional distillation utilises the different boiling points of the many different compounds present in petroleum to separate them. The separated fractions can then be used as fuel or can be treated to produce desired products. For the context of this study design, it is not necessary to know this process in detail.

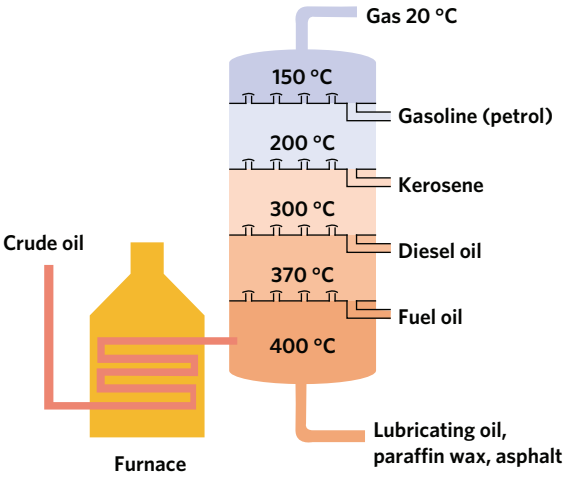


Figure 4 Stages of fractional distillation of crude oil, with the common uses of each fraction

KEEN TO INVESTIGATE?

1 **What fuel should you use in your car?**
Search YouTube: Fuel octane rating explained

A useful product of the fractional distillation of crude oil is petrol.[1] Petrol contains a mixture of hydrocarbon molecules, including octane (figure 5), that range in length from 5 to 12 carbon atoms. Whilst petrol itself consists purely of hydrocarbons, implying that burning it should only release carbon dioxide and water, petroleum deposits are often contaminated with hydrogen sulfide (H_2S) and other sulfur and nitrogen compounds. When petrol contaminated with sulfur is burned, it produces harmful sulfur dioxide, making it less desirable as a fuel due to its negative effects on the environment.

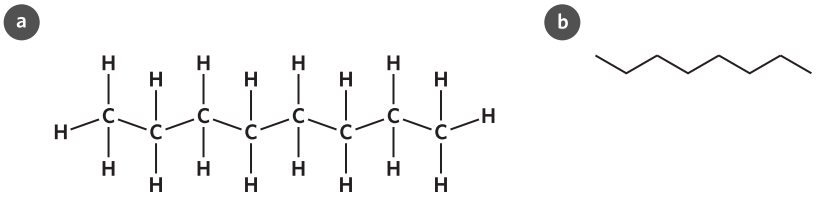


Figure 5 Example of a common molecule that makes up petrol (octane, C_8H_{18}) **(a)** full structural **(b)** skeletal

KEEN TO INVESTIGATE?

2 **Why has fracking been banned in Victoria?**
Search: Victoria becomes first Australian state to ban fracking

Coal seam gas (natural gas), like petroleum and coal, is formed from the remains of plants and animal materials. It is found in deposits in the Earth's crust and can be accessed by drilling. It is then extracted from coal and shale deposits by a process known as fracking. Fracking involves injecting liquid at high pressure into coal and shale rocks to force open fissures (cracks) to extract the gas. Materials used for this process have harmful impacts on the surrounding environment as well as water supplies.[2]

Coal is the most common source used to generate electricity, followed by petroleum-powered and natural gas-powered plants. However, at the current rates of consumption, coal, crude oil, and coal seam gas won't be available indefinitely. As these resources are limited, it is important to find alternative sources of energy and to consider the impact of burning these fuels on the environment.

WORKED EXAMPLE 1

Select the set of fuels that contain the three major sources of energy currently used by society.

A. Coal, wood, and oil
B. Nuclear, coal, and oil
C. Peat, coal seam gas, and natural gas
D. Coal, oil, and natural gas

What information is presented in the question?
Different types of fuels.

What is the question asking us to do?
Decide which fuels are the most commonly utilised by society.

What strategies do we need in order to answer the question?
1. Cross out the fuels that are not commonly used.
2. Confirm that the option remaining has commonly used sources.

Answer
Option A: Wood is not commonly used in society.
Option B: Nuclear energy is not commonly used in society.
Option C: Peat is not commonly used in society.
Option D: All three of coal, oil and natural gas are commonly used in society.

PROGRESS QUESTIONS

Question 1
Which of the following is not considered to be a fuel?
A. Petrol
B. Wood
C. Sand
D. LPG

Question 2
Chemical reactions caused by _____ initiate the transformation of decaying plant and marine creatures' remains into hydrocarbons.
A. water vapour
B. decomposition
C. oxygen gas
D. solar energy

Question 3
Coal seam gas can be best described as
A. being formed from animals only.
B. being formed from plants only.
C. a single hydrocarbon compound.
D. a mixture of small hydrocarbon compounds.

MISCONCEPTION

'Nuclear fuel is a fossil fuel and is renewable.'

Nuclear fuel (e.g. uranium ore) is not formed by the same processes as fossil fuels, and once the nuclear fuel is used, it cannot be replaced by natural processes in a short period of time.

Non-renewability of fossil fuels 3.1.1.2

Although fossil fuels are formed by natural processes, the resources that produce them are not quickly replenished, therefore making them **non-renewable resources**.

Why are fossil fuels non-renewable?

A non-renewable resource is a substance that cannot be replaced by natural processes at the same rate, or faster than it is consumed. Coal, petroleum and coal seam gas are produced from organic material that has undergone complex natural decomposition processes that take millions of years to occur. Therefore, they cannot be replaced in the foreseeable future. These fuels (coal, petroleum and coal seam gas) are classified as non-renewable because they are being used up faster than they can be replaced.

This is a problem in our constantly growing world as the demand for fuel increases with a rising population using fuel-dependent technology. Moreover, the extraction methods of each of these fuels are harmful to the environment in different ways, making finding alternative fuels more desirable. For example sulfur dioxide (SO_2) emissions from the burning of coal and contaminated petrol contribute to the formation of acid rain. Fossil fuel-fired electric power stations emit a large amount of carbon dioxide which accumulates in the atmosphere. This accumulation of gases in the atmosphere contributes to what is known as the **enhanced greenhouse effect**, where more thermal energy is trapped by the atmosphere, causing the planet to become warmer than it would normally be.

The process of drilling and mining for coal, coal seam gas and crude oil disrupts the natural landscape and can disrupt the water table if spills occur. Therefore, fuels from resources that are renewable and less harmful to the environment are very desirable alternatives. These alternative resources are known as biofuels and will be discussed in lesson 1B.

PROGRESS QUESTIONS

Question 4

Which of the following is a correct statement regarding fossil fuels?

A. All fossil fuels are non-renewable resources.

B. All non-renewable energy sources are fossil fuels.

C. Fossil fuels are renewable resources.

D. All renewable energy sources are fossil fuels.

Question 5

Which statement(s) regarding petrol is/are correct?

Petrol is

I. extracted directly from the ground.

II. non-renewable.

III. separated from crude oil.

A. III only

B. II and III only

C. All of the above

D. None of the above

Continues →

Question 6

Which of the following problems could be a result of the combustion of coal?

A. Carbon dioxide emissions

B. Acid rain formation

C. Carbon smog

D. All of the above

Theory summary

- A fuel is a substance that is combusted to produce energy in the form of heat.
- Coal, which is mined from the ground and combusted in power plants for electricity, is formed by the natural breakdown of organic materials.
- Crude oil, found in reservoirs in porous rocks, is separated by fractional distillation to obtain petrol and other useful hydrocarbons.
- Petrol is a hydrocarbon obtained from crude oil.
- Coal seam gas (natural gas) is formed from the remains of plants and animals and is combusted in power plants for electricity.
- Fossil fuels, such as natural gas, coal and petrol, are non-renewable energy sources that are formed by natural processes over millions of years.
- A fuel is considered to be non-renewable if it cannot be replaced by natural processes within a relatively short period of time.
- A fossil fuel is not sustainable as it cannot be produced at a rate that is greater than its consumption.

1A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

Methane gas may be obtained from a number of different sources. It is a major component of natural gas. Methane trapped in coal is called coal seam gas and can be extracted by a process known as fracking. Methane is also produced by the microbial decomposition of plant and animal materials. In addition, large reserves of methane were trapped in ice as methane hydrate in the ocean depths long ago.

Question 7 (1 MARK)

When is a fuel considered a non-renewable resource?

A. If there is a surplus in the supplies of the fuel

B. If there is a greater demand than supply of the fuel

C. If it cannot be replaced by natural processes within a relatively short period of time

D. If it can be replaced by natural processes within a relatively short period of time

Question 8 (1 MARK)

Fossil fuels take approximately

A. 1 year to be replaced.

B. 10 years to be replaced.

C. 100 years to be replaced.

D. 1 000 000+ years to be replaced.

Question 9 (3 MARKS)

Explain whether methane is a non-renewable energy source when it is obtained from each of the sources outlined in the paragraph.

Adapted from VCAA 2014 exam Multiple choice Q24

Exam-style

Question 10 (1 MARK)

Crude oil is used as a fuel for transportation, heating and electricity. Which of the following best describes crude oil?

A. A naturally occurring solid found in coal deposits

B. An artificial oil created in labs

C. A naturally occurring liquid composed of hydrocarbons

D. Liquid produced from anaerobically fermenting plant material

Question 11 (7 MARKS)

Natural gas and coal are both examples of fuel sources that can be used to produce energy.

a. Identify whether coal and natural gas are classified as fossil fuels, giving a justification for your response. 4 MARKS

b. Ethanol can be produced from coal. Identify whether ethanol produced using this method can be considered non-renewable. 3 MARKS

Question 12 (3 MARKS)

Wood cannot be grown at the rate at which we are using it.

a. Why is wood not considered a fossil fuel? 2 MARKS

b. Identify why sourcing energy from wood is considered an unsustainable process, even though wood can be replaced by natural processes within a relatively short period of time. 1 MARK

Key science skills

Use the following information to answer question 13.

Article 1

Whenever any global summits about climate change occur, fossil fuels are almost always at the centre of the talks. The main three being oil, coal and natural gas. It is predicted that we will run out of certain fossil fuels at some point during this century. Recent predictions are:

- oil ≈ 50 years
- natural gas ≈ 53 years
- coal ≈ 114 years.

Based on the targets set by the Intergovernmental Panel on Climate Change (IPCC), some recommendations are:

- Nations must make immediate and deep cuts in the production of all fossil fuels, including a rapid and just phaseout of existing production.
- Coal production in developed nations (like Australia) needs to fall by 50% within five years and be effectively eliminated by 2030.
- Output of oil and gas in developed nations needs to be cut by 74% by 2030, with a complete phaseout by 2034.

Article 2

As oil and gas become harder to access and renewable sources become more commonly used, it will make more financial sense to leave fossil fuels in the ground and switch to cleaner, renewable sources instead. Thinking we will simply switch to renewable energy sources when fossil fuels run low is hugely naïve. To avoid the worst impacts of climate change, fossil fuel reserves need to be left in the ground. Some people think that as we use more oil and gas, the reserves will run lower. They hadn't realised that as technology improves, it becomes possible to find and extract more fossil fuels.

Source: (2022). *Fossil Fuel Reserves Aren't Running Out*. Gapminder. *gapminder.org/lessons/fossil-fuel-reserves-arent-running-out*

Question 13 🌶🌶 (6 MARKS)

a. Which of the articles would be considered opinion? Justify your answer. 2 MARKS

b. Give one factor that would prevent Australia from carrying out the recommendations outlined in Article 1. Explain your reasoning. 2 MARKS

c. Give a different factor that would prevent Australia from carrying out the recommendations outlined in Article 1. Explain your reasoning. 2 MARKS

FROM LESSONS 12B & 12C

Back to contents

1B Biofuels

STUDY DESIGN DOT POINTS

- the definition of a fuel, including the distinction between fossil fuels (coal, natural gas, petrol) and biofuels (biogas, bioethanol, biodiesel) with reference to their renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)
- production of bioethanol by the fermentation of glucose and subsequent distillation to produce a more sustainable transport fuel: $C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$

1A 1B 1C 1D

3.1.1.3 & 3.1.1.4 Definition of biofuels & renewability of biofuels

3.1.5.1 Production of bioethanol

ESSENTIAL PRIOR KNOWLEDGE

1A Non-renewable resource

See question 4.



Image: Jim Barber/Shutterstock.com

Why are biofuels not more commonly used?

The expenses are often greater for producing **biofuels** when compared to fossil fuels, and this is an area scientists are researching in order to make biofuel production cheaper and more environmentally friendly. Biofuels are a broad category of fuels sourced from organic matter and are an alternative source of energy to fossil fuels. In this lesson, we will explore the renewability and sustainability of different types of biofuels.

KEY TERMS AND DEFINITIONS

Biodiesel fuel produced by the transesterification of fats and oils in organic matter

Bioethanol fuel produced by the anaerobic fermentation of glucose from organic matter

Biofuel fuel sourced from organic matter

Biogas gaseous fuel produced by the anaerobic breakdown of organic matter

Biomass any organic material made of plant or animal matter

Carbon neutral describes a fuel that does not result in a net production of carbon dioxide from sourcing and consumption

Distillation process involving the conversion of a liquid into vapour that is then condensed back to liquid form

Feedstock raw material used for producing another product

Fermentation breakdown of a substance in the presence of microorganisms such as yeast

Life cycle the management of the production, processing, storage, transportation, use, and disposal of a chemical product

Renewable resource resource capable of being replaced by natural processes within a relatively short period of time

Transesterification reaction a type of chemical reaction used to produce biodiesel and glycerol

Triglyceride fat or oil composed of three fatty acid tails and a glycerol backbone

Yeast variety of microorganism which converts glucose into ethanol

Definition of biofuels & renewability of biofuels 3.1.1.3 & 3.1.1.4

In light of our changing climate, Australian leaders and industry are investigating a range of energy sources to replace fossil fuels. Biofuels may provide a viable alternative. We can use our knowledge of the source of a biofuel to determine if it is a **renewable resource** and/or a sustainable resource.

What is a biofuel?

A biofuel is a fuel sourced directly from organic matter, such as sugarcane, soya beans, wheat, or vegetable oils. The three main types of biofuels we will study are **biogas**, **biodiesel** and **bioethanol**.

WORKED EXAMPLE 1

Explain why methane sourced from natural gas deposits is considered a fossil fuel, but methane sourced from the decomposition of vegetable waste is considered a biofuel.

What information is presented in the question?

Methane in natural gas is a fossil fuel.

Methane sourced from vegetable waste decomposition is a biofuel.

What is the question asking us to do?

Explain the relationship between how a fuel is sourced and its classification.

What strategies do we need in order to answer the question?

1. Identify the characteristics of methane in natural gas that make it a fossil fuel.
2. Identify the characteristics of methane sourced from vegetable waste that make it a biofuel.

Answer

Methane derived from natural gas is produced by the chemical decomposition of animal and plant remains over a very long period of time, so it is considered a fossil fuel. Methane derived from the decomposition of vegetable scraps is directly obtained from organic matter, so it is considered a biofuel.

How is biogas made?

As shown in figure 1, organic matter (such as algae, crops, wood, or compostable organics) is broken down by bacteria into gas. This process is described as anaerobic, because it does not require oxygen to proceed.

The gas that is produced is a mixture of different gases: predominantly methane, but also a large proportion of carbon dioxide. Every sample of biogas will contain different proportions of gases; figure 2 shows an approximation of the average proportions of different gases in biogas.

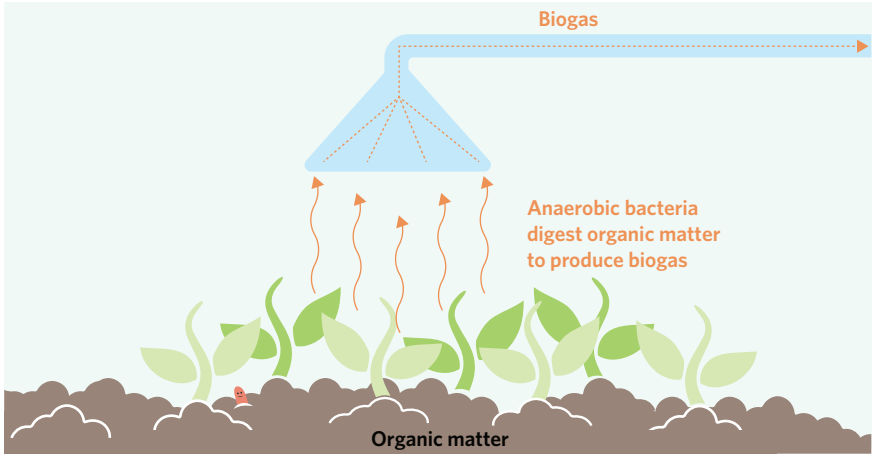


Figure 1 The production of biogas from organic matter

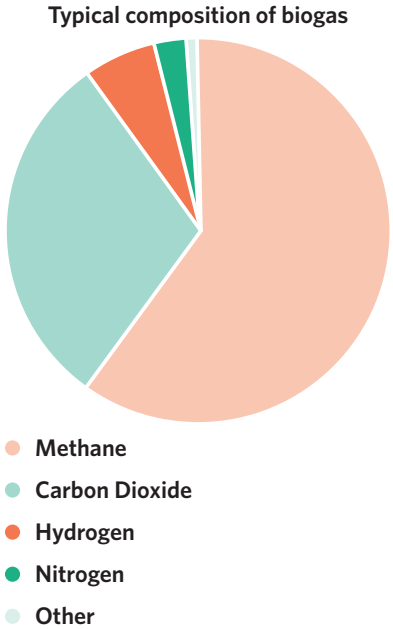


Figure 2 An example of the composition of a biogas

How is biodiesel made?

Biodiesel is produced by a **transesterification reaction** of fats originating from animal products, and oils originating from crops. Animal fats and plant oils, such as sunflower and canola, are composed of compounds known as **triglycerides**.
An alcohol, usually methanol, is added to the triglyceride, and with a catalyst such as potassium hydroxide, it reacts to form biodiesel, a mixture of fatty acid methyl esters (figure 3).

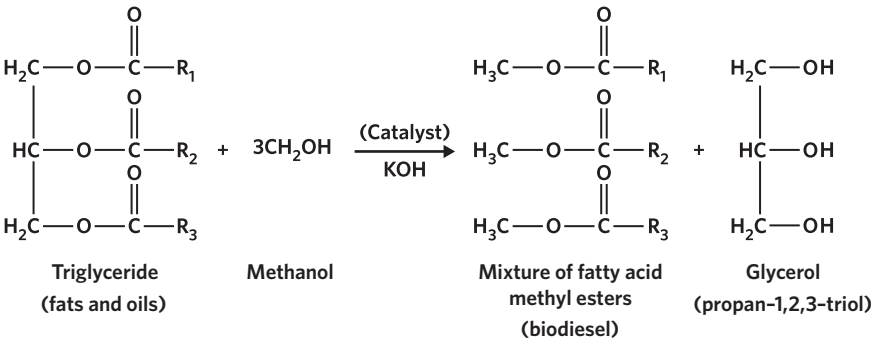


Figure 3 Transesterification of triglycerides

The reaction shown in figure 3, as well as other organic reactions, conditions, and structures, will be explored further in chapter 8.

Why are biofuels considered renewable?

We have already learned the definition of a non-renewable fuel in lesson 1A. A fuel is considered a renewable resource if it is capable of being replaced by natural processes within a relatively short period of time. For example, the fatty acid methyl esters we know as biodiesel are derived from crops and animal fats which can be produced in less than a year to replenish supplies. As a result, we classify biodiesel as a renewable energy source.

Similarly, biogas is produced directly from organic matter, meaning it can be produced in a relatively short time period. For this reason, biogas is also classified as a renewable energy source.

USEFUL TIP

R is an abbreviation that is used in organic chemistry for any hydrocarbon chain (e.g. $-CH_2CH_3$) or hydrogen atom attached to the rest of the molecule. This helps simplify what is occurring in reactions.

USEFUL TIP

Renewability concerns the period of time to replace resources, whereas sustainability concerns the rate of production versus the rate of consumption of resources.

PROGRESS QUESTIONS

Question 1

Biogas is mainly composed of _____ and is a _____ energy source.

A. carbon dioxide, renewable
B. methane, non-renewable
C. carbon dioxide, non-renewable
D. methane, renewable

Question 2

Renewable fuels

A. release less carbon dioxide than non-renewable fuels.
B. are replaced at least at the rate at which they are consumed.
C. directly contribute less to global warming than non-renewable fuels.
D. are all biofuels.

Continues →

Question 3

Which one of the following statements best defines a renewable energy resource?

A. An energy resource that will not be consumed within our lifetime

B. An energy resource that does not produce greenhouse gases when consumed

C. An energy resource derived from plants that are grown for the production of liquid biofuels

D. An energy resource that can be replaced by natural processes within a relatively short time

VCAA 2015 exam Multiple choice Q5

Production of bioethanol 3.1.5.1

Bioethanol is one of the main biofuels used in the transportation industry. It is estimated that transport fuels in Australia account for 25% of all energy used per year.

How can bioethanol be produced on an industrial scale and used for transport?

A solution of bioethanol is produced by the anaerobic **fermentation** of glucose (a sugar) in organic matter (**biomass**) by a microorganism called **yeast**, as shown in figure 4a. This solution of bioethanol then undergoes **distillation**, removing the water to create pure bioethanol, as shown in figure 4b. Organic matter commonly fermented by yeast includes crops such as sugarcane, soybeans, and corn. Ethanol is only considered bioethanol when produced via the fermentation and distillation process described in figure 4c.

MISCONCEPTION

'Solutions of bioethanol are not flammable.'

A solution of bioethanol that contains 20 mL of bioethanol per 100 mL of water is still flammable.

a

Fermentation

Glucose solution	Yeast → 32–35°C Anaerobic	Bioethanol solution	+	Carbon dioxide gas
$C_6H_{12}O_6(aq)$	→	$2C_2H_5OH(aq)$ 5–21% v/v	+	$2CO_2(g)$

b

Distillation

Bioethanol solution	Water removed → >100°C	Pure bioethanol liquid (can be added to petrol)
$2C_2H_5OH(aq)$ 5–21% v/v	→	$2C_2H_5OH(l)$ 100% v/v

c

Overall equation

$C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$

Figure 4 **(a)** Fermentation process of glucose into bioethanol **(b)** subsequent distillation and **(c)** the overall equation

MISCONCEPTION

'Fermentation of glucose and other sugars only produces bioethanol.'

Many other compounds are also formed in small quantities, including ethanoic acid, ethanal, esters, and higher alcohols.



Image: koonsiri boonnak/Shutterstock.com

Figure 5 Since 2007, E25 (25% bioethanol) is the minimum blend allowed in Brazil.

E10, a blend of 10% bioethanol and 90% petrol, is a common fuel available at some service stations in Australia and is the most prominent biofuel already in the mainstream Australian market. Other countries are far ahead of Australia; for example, most automobiles in Brazil run either on E85 or E25 blend (figure 5).

Although the combustion of bioethanol produces $CO_2(g)$, the process of crop production offsets this release through the absorption of $CO_2(g)$ from plants undergoing photosynthesis (covered in lesson 1C). This means bioethanol is considered relatively **carbon neutral**, as shown in figure 6. However, it is not completely carbon neutral because the processes involved, such as the transportation, harvesting, and production of organic matter, all require energy (figure 7).

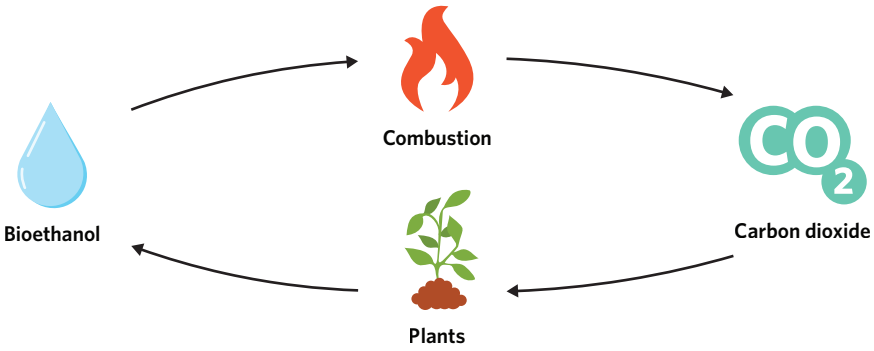


Figure 6 The recycling of carbon dioxide in the production of bioethanol

USEFUL TIP

Non-renewable industrial pure ethanol is made from ethene (CH_2CH_2) which comes from crude oil. The addition reaction of ethene with steam in the presence of an acid catalyst is covered in chapter 8.

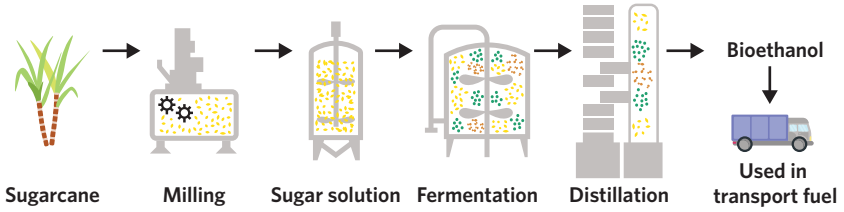
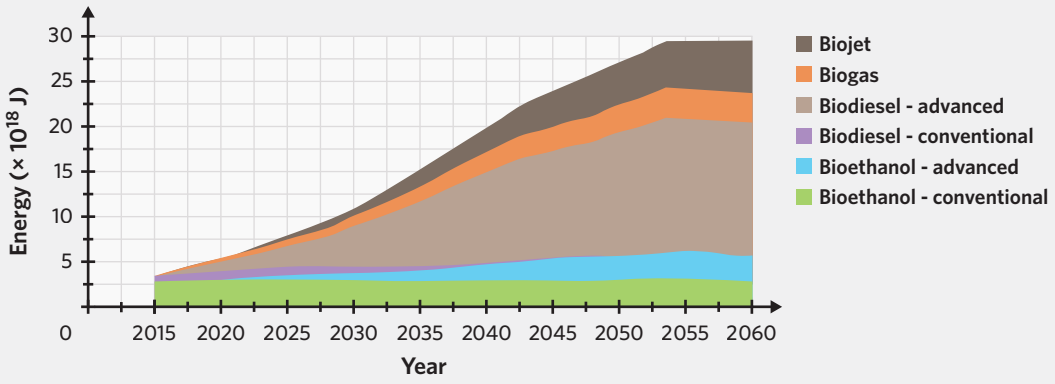


Figure 7 Simplified overview of the process of producing bioethanol

WORKED EXAMPLE 2

What qualitative conclusion can be drawn from the following graph regarding the predicted future demand for bioethanol versus biodiesel for use in transport?



Continues →

What information is presented in the question?

Global biofuels' energy growth compared to the type of fuel.

What is the question asking us to do?

Draw a qualitative conclusion by first comparing the data shown in the graph.

What strategies do we need in order to answer the question?

1. Identify the trends for bioethanol (conventional and advanced).
2. Identify the trends for biodiesel (conventional and advanced).
3. Compare the future trendlines.

Answer

Although predicted demand for advanced bioethanol increases from 2025 to 2060 (whereas predicted demand for conventional bioethanol remains steady), this increase is much smaller than that of the predicted demand for advanced biodiesel (although conventional biodiesel is predicted to be phased out by 2045). Biodiesel (advanced) is depicted as the biofuel of the future, predicted to constitute a far larger share of the fuel market than bioethanol by 2060.

How sustainable are biofuels?

Sustainable and environmentally friendlier energy (based on the use of renewable resources) is necessary in order to meet the future energy needs of humans. For example, the use of bioethanol in blended fuels is a more sustainable option than petrol, as crops can be grown again to produce more bioethanol in a short period of time (months). However, the whole **life cycle** of biofuels is not completely carbon neutral, and the production and use of biofuels does require certain considerations.

Food vs fuel

The production of biofuels should not reduce the amount of food available to the growing global population, and the **feedstock** must be sourced from waste products of food crops or non-edible plant waste materials like sugarcane pulp (bagasse).[1]

KEEN TO INVESTIGATE?

[1] **How can the waste from sugarcane help reduce plastic pollution?**
Search YouTube: Biodegradable sugarcane bagasse manufacture

Land requirements

Researchers estimate that Australians will need around 100 million hectares of land (the size of China) to grow enough biofuels to both reduce carbon emissions and shift to a greener economy in the next 30–40 years.

Energy input vs energy output

The total amount of energy required to grow, collect, and convert the feedstock into a usable biofuel should only represent a small percentage of the total energy available from combustion of the biofuel. Industrial processes are continuously improving efficiency: a key factor in improving the sustainability of biofuel energy production. It is crucial that the amount of energy input to create these biofuels is reduced, which can be achieved using more efficient biofuels that will help the transition more towards the use of alternative fuels, given they are both sustainable and more environmentally friendly than conventional fossil fuels.

MISCONCEPTION

'Bioethanol made from plants is different to ethanol produced from crude oil.'

Ethanol is ethanol; it functions the same, regardless of the source.

PROGRESS QUESTIONS

Question 4

What could be considered a carbon neutral activity?

Any activity that

A. releases no net carbon dioxide.

B. produces carbon dioxide.

C. does not involve carbon.

D. does not produce carbon.

Continues →

Question 5

Which one of the following is a biofuel?

A. Ethanol produced from crude oil

B. Ethanol produced from plants

C. Propane produced from natural gas

D. Electricity produced by nuclear power

Adapted from VCAA 2017 exam Multiple choice Q5

Question 6

Which statement about the production of bioethanol is incorrect?

A. Bioethanol is produced via anaerobic fermentation.

B. Once the bioethanol has been fully distilled, it can be considered a pure liquid.

C. The fermentation of glucose yields a high percentage by volume of bioethanol.

D. Energy from the feedstock used to produce ethanol is initially stored as fat.

Theory summary

- A biofuel is a fuel sourced directly from plant and/or animal matter.
- Biogas is a mixture of gases produced by the anaerobic breakdown of organic matter.
- Bioethanol is a fuel produced by the fermentation and the subsequent distillation of glucose or other sugars found in organic matter.
- Biodiesel is a fuel produced by the transesterification of fats and oils.
- A fuel is renewable if it can be replaced by natural processes within a relatively short period of time.
- Biofuel production has advantages and disadvantages when compared to fossil fuels.
- A biofuel is sustainable if it can be produced at a rate that is greater than consumption without compromising future generations.

1B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

Bioethanol can be easily made in Australia using waste from the sugarcane industry.

Question 7 (1 MARK)

What is one disadvantage of the production and use of bioethanol?

A. It can be viewed as carbon neutral.

B. Fertile land is needed for crops.

C. It is a renewable resource.

D. It utilises waste biomass.

Question 8 (1 MARK)

What is one advantage of bioethanol?

A. Biofuel crops can be grown in months.

B. Fertile land is needed for crops.

C. Bioethanol is expensive compared to other fuels.

D. It is non-renewable.

Question 9 (4 MARKS)

In simple terms, biofuels can be considered to be carbon neutral, as the carbon dioxide taken in by the plants when they are growing is equal to the amount given off when the biofuel is combusted. In reality, many other factors are involved.

a. Give an example of a factor and explain why it is difficult to have a truly carbon neutral fuel. 2 MARKS

b. Give a different example of a factor and explain why it is difficult to have a truly carbon neutral fuel. 2 MARKS

Exam-style

Question 10 (1 MARK)

Which of the following compounds is a mixture of methyl esters?

A. Methane **B.** Bioethanol **C.** Biodiesel **D.** Triglycerides

Question 11 (1 MARK)

Which of the following statements is most correct?

A. Biogas is derived from the chemical decomposition of anaerobic bacteria.

B. Fatty acid methyl esters are created by the oxidation of fats.

C. Methane sourced from the breakdown of compost is a renewable energy source.

D. Bioethanol can be obtained from the fractional distillation of crude oil.

Question 12 (5 MARKS)

Daisy purchases a new car, only to discover the fuel required is pure biodiesel. Unfortunately, there are no local biodiesel service stations, and so Daisy decides to produce biodiesel from the local sunflower crops, which grow very quickly. They also know that they will not require all the sunflower crops to power their car.

a. Would biodiesel produced in this way be considered renewable? Explain your answer. 2 MARKS

b. List an environmental concern Daisy may have regarding the process, with respect to water. 1 MARK

c. Daisy adds methanol and a catalyst to the oil extracted from the sunflower crops.
What type of reaction is occuring? 1 MARK

d. Daisy is successful in creating their desired product, yet notices an additional product is formed.
What is the name of this product? 1 MARK

Question 13 (5 MARKS)

Sugarcane is a species of tall grass rich in glucose. When fermented by anaerobic bacteria, the following reaction occurs:

$C_6H_{12}O_6(aq) \rightarrow 2X(aq) + 2Y(g)$

a. Name compounds X and Y. 1 MARK

b. Explain why compound X is considered a renewable fuel. 1 MARK

c. The above reaction produces compound Y, but this is offset by the production of sugarcane crops.
Explain one environmental impact of compound Y if it were not offset. 1 MARK

d. Glucose for the above reaction is now sourced from potatoes. Would compound X still be defined as renewable? 2 MARKS

Key science skills

Question 14 (6 MARKS)

Climate change has been identified as a threat to the environment. Fossil fuels are recognised as a significant contributor to the rise in carbon dioxide levels in the atmosphere. The replacement of fossil fuels as an energy source represents a challenge and has been the focus of research for a number of years. However, there are different opinions/views about the suitability of using a biofuel, such as bioethanol, as a replacement for fossil fuels. Some extracts representing different viewpoints are shown in the box below.

[1]'Biofuels are fuels that are produced from biological sources such as trees, plants or microorganisms. They are carbon neutral, because they do not result in fossil carbon being released into the atmosphere.'

[2]'All good solutions are needed in the energy transition required to achieve Europe's climate goals and sustainable biofuels are critical to transport decarbonisation.'

[3]'Many scientists view biofuels as inherently carbon neutral: they assume the carbon dioxide (CO_2) plants absorb from the air as they grow completely offsets, or 'neutralises,' the CO_2 emitted when fuels made from plants burn.'

[4]'... our analysis affirms that, as a cure for climate change, biofuels are 'worse than the disease.'

[5]'... although some forms of bioenergy can play a helpful role, dedicating land specifically for generating bioenergy is unwise.'

Sources: [1]CarbonNeutralEarth, <www.carbonneutralearth.com/biofuels.php>; [2]Sejersgård Fanø, quoted in Erin Voegele, '*EU reaches deal on REDII, sets new goals for renewables*', Biodiesel Magazine, 15 June 2018, <www.biodieselmagazine.com>; [3 &4]John DeCicco, '*Biofuels turn out to be a climate mistake– here's why*', The Conversation, 5 October 2016, <www.theconversation.com/au>; [5]Andrew Steer and Craig Hanson, '*Biofuels are not a green alternative to fossil fuels*', The Guardian, 30 January 2015, <www.theguardian.com/au>

Using the chemistry that you have studied and the information provided, discuss the carbon neutrality and the sustainability of using bioethanol as a fuel for transport. In your answers, give arguments for and against under the following headings:

a. Carbon dioxide 2 MARKS

b. Sustainability of using bioethanol as a fuel 2 MARKS

c. Using bioethanol as a fuel for transport 2 MARKS

Adapted from VCAA 2019 exam Short answer Q10a

FROM LESSON 12E

Questions from multiple lessons

Question 15 (1 MARK)

Which one of the following fuels is the most sustainable?

A. Biodiesel

B. Uranium

C. Coal

D. Natural gas

Adapted from VCAA 2012 Exam 2 Multiple choice Q2

FROM LESSON 1A

Question 16 (1 MARK)

Which of the following alternatives lists only renewable energy resources?

A. Coal, diesel, ethanol

B. Coal, crude oil, uranium

C. Ethanol, methane, diesel

D. Crude oil, natural gas, ethanol

VCAA 2013 Exam 2 Multiple choice Q22

FROM LESSON 1A

Question 17 (1 MARK)

Digesters use bacteria to convert organic waste into biogas, which contains mainly methane, CH_4. Biogas can be used as a source of energy. Both biogas and coal seam gas contain CH_4 as their main component.

Why is biogas considered a renewable energy source but coal seam gas is not?

VCAA 2021 exam Short answer Q1a

FROM LESSON 1A

Question 18 (1 MARK)

Which one of the following statements is correct?

A. Crude oil can be classified as a biofuel because it originally comes from plants.

B. Methane, CH_4, can be classified as a fossil fuel because it has major environmental impacts.

C. Ethanol, CH_3CH_2OH, can be classified as a fossil fuel because it can be produced from crude oil.

D. Hydrogen, H_2, can be classified as a biofuel because, when it combusts, it does not produce carbon dioxide, CO_2.

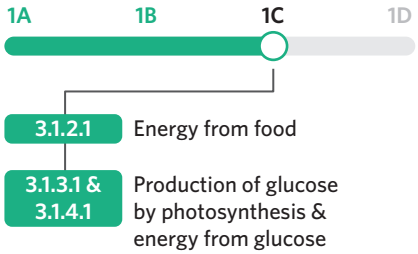
VCAA 2020 exam Multiple choice Q11

FROM LESSON 1A

1C Fuel for the body

STUDY DESIGN DOT POINTS

- fuel sources for the body measured in kJ g^{-1}: carbohydrates, proteins and lipids (fats and oils)
- photosynthesis as the process that converts light energy into chemical energy and as a source of glucose and oxygen for respiration in living things: $6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$
- oxidation of glucose as the primary carbohydrate energy source, including the balanced equation for cellular respiration: $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$



ESSENTIAL PRIOR KNOWLEDGE

- Polymers
- Oxidation reactions

See questions 5–6.



Image: Elena Eryomenko/Shutterstock.com

Why do some types of food contain more energy than others?

Together, **photosynthesis** and **cellular respiration** form a continuous cycle that sustains life on Earth. Photosynthesis produces the oxygen needed for cellular respiration in animals and humans, while cellular respiration produces the carbon dioxide that plants need for photosynthesis. Many complex processes are involved in supplying oxygen to breathe, and energy from different types of food for our bodies. In this lesson we will simplify two major processes that allow Earth to be inhabited by organisms.

KEY TERMS AND DEFINITIONS

Carbohydrate any polymer made up of sugar monomers like glucose

Cellular respiration process of converting glucose into energy in the cells of living organisms

Digestion a series of complex processes involved in the breakdown of food

Energy content amount of heat energy (in joules or kilojoules) produced upon burning 1 gram of a pure substance

Glucose ($C_6H_{12}O_6$) an important sugar that is absorbed into the bloodstream and transported to cells

Metabolism chemical reactions in the body's cells that change food into energy

Photosynthesis process of converting light energy into chemical energy in the cells of plants, algae, and certain bacteria

Energy from food 3.1.2.1

Food plays an integral role in our survival. **Metabolism** of food not only gives us molecules critical to our biological functioning, but also provides us with energy to sustain all of the reactions required for us to survive.

How much energy can different types of food provide to the body?

Proteins, **carbohydrates**, and fats all have a different **energy content**; that is, they provide us with a different amount of energy per gram metabolised.

This is due to the different types of bonds that are broken and formed when they are metabolised. As outlined in table 1, fats and oils provide the greatest amount of energy per gram, followed by proteins and lastly carbohydrates. The human body constantly breaks down certain carbohydrates and fats/oils as a supply of energy.

Table 1 Energy content of food groups

Food	Heat of combustion (kJ g^{-1})
Fat and oils	37
Protein	17
Carbohydrate	16

USEFUL TIP

Due to the fact that food is a mixture of different substances, the energy content is expressed in kilojoules per gram (kJ g^{-1}) rather than per mole.

As we know, foods contain more than just fats, proteins, and carbohydrates. For example, many cereals contain fibre, which is an indigestible form of carbohydrate and therefore does not provide the body with any energy. As a result, when calculating the energy content of food, we mainly focus on the three main food groups highlighted in table 1. This will be covered in more detail in lesson 2C.

PROGRESS QUESTIONS

Question 1

Compared to fats and oils and carbohydrates, proteins contain

A. the most amount of energy per gram.

B. the least amount of energy per gram.

C. more energy than fats but less energy than carbohydrates per gram.

D. more energy than carbohydrates but less energy than fats per gram.

Production of glucose by photosynthesis & energy from glucose 3.1.3.1 & 3.1.4.1

The main source of energy for our planet is the sun, the light of which powers photosynthesis. **Glucose** is an essential molecule that serves as the primary source of energy for almost all living organisms, through a process called cellular respiration. It is a type of carbohydrate that plants produce through photosynthesis. Glucose, photosynthesis, and cellular respiration are fundamental to the survival and sustainability of life on our planet.

What is photosynthesis?

Photosynthesis is the process by which plants, algae, and certain bacteria convert light energy from the sun into chemical energy in the form of organic compounds, such as glucose. This process involves the absorption of light by the green pigment chlorophyll in the chloroplasts of plant cells, which is then used to split water molecules into oxygen and hydrogen ions. The hydrogen ions and electrons are then used to build carbohydrates (sugars) from carbon dioxide in a series of complex biochemical reactions. This process is responsible for the production of oxygen in the atmosphere and is the basis of all life on Earth (figure 1).

$$\text{Carbon dioxide} + \text{Water} + \text{Solar energy} \rightarrow \text{Glucose} + \text{Oxygen}$$

$$6CO_2(g) + 6H_2O(l) + \text{Solar energy} \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$$

Figure 1 Equation for photosynthesis

KEEN TO INVESTIGATE?

1 What happens when glucose can't be broken down into energy?
Search YouTube: What Is Diabetes? 2 Minute Guide

What is cellular respiration?

Respiration is the process by which organisms convert glucose into energy. This process occurs in both plants and animals and allows them to use energy from glucose to power cellular processes such as growth, reproduction, and movement. Glucose is absorbed into the bloodstream and transported to cells, where the process of cellular respiration converts this molecule into energy.[1]

The polymers found in food are broken down into monomers such as glucose by the process of **digestion**; they are then converted into energy by an oxidation process known as cellular respiration. The equation for this reaction is given in figure 2.

Glucose + Oxygen → Carbon dioxide + Water + Chemical energy

$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$ + Chemical energy

Figure 2 Equation for cellular respiration

KEEN TO INVESTIGATE?

2 How does the rate of burning fuels (combustion and respiration) vs the amount of photosynthesis taking place affect the Earth's climate?
Search videos: Too much combustion we need more photosynthesis

How do photosynthesis and cellular respiration compare?

From figures 1 and 2, we can see that the reactions for photosynthesis and cellular respiration are fundamentally the reverse of each other. Table 2 and figure 3 show how these processes compare to each other.[2]

Table 2 Comparison of cellular respiration and photosynthesis

Cellular Respiration	vs	Photosynthesis
In all living organisms	**In which organisms does it occur?**	In all green plants, algae, and some bacteria
In mitochondria	**Where in the cell does it occur?**	In chloroplasts
Glucose solution and oxygen	**What are the reactants?**	Carbon dioxide, water, and light energy
Carbon dioxide, water, and chemical energy	**What are the products?**	Glucose solution and oxygen
It is broken down.	**What happens to the glucose?**	It is created.
Oxygen is taken in with food (chemical energy in glucose); carbon dioxide and energy are produced.	**What is the overall change?**	Produces food (glucose) by converting light energy into chemical energy
It is an exothermic reaction as energy is released.	**What is the energy change for the reaction?**	It is an endothermic reaction as it requires an energy input.
$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$	**What is the overall chemical equation?**	$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

Researchers are currently investigating how an artificial photosynthetic series of reactions can be used to produce greener fuels; this is covered in more detail in lesson 6D.

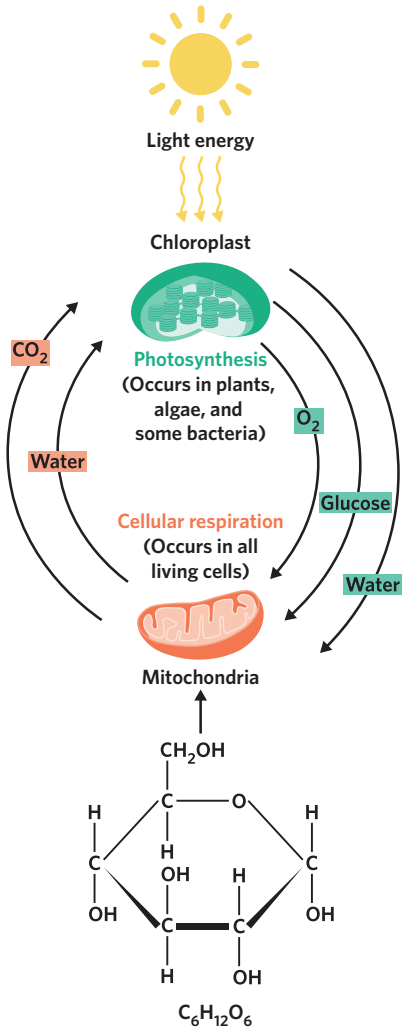


Figure 3 Simple overview of photosynthesis and cellular respiration

WORKED EXAMPLE 1

Write a simple summary sentence that compares the similarities of both the reactants and products of cellular respiration and photosynthesis.

What information is presented in the question?

The two processes that need to be compared in terms of their reactants and products.

What is the question asking us to do?

Compare reactants and products of the two processes and construct a sentence to summarise these.

What strategies do we need in order to answer the question?

1. Write out the chemical equations for both reactions.
2. Construct a summary sentence about the similarities.

Answer

Cellular respiration: $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$

Photosynthesis: $6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

Both of these processes cycle the same four molecules: carbon dioxide, oxygen, glucose, and water.

PROGRESS QUESTIONS

Question 2

Cellular respiration and photosynthesis both require

A. carbon dioxide.

B. water.

C. sugar.

D. oxygen.

Theory summary

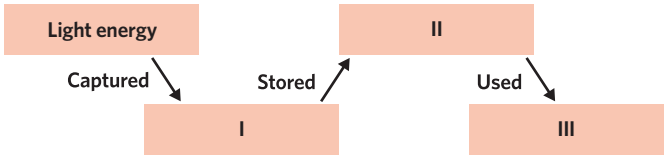
- Energy in food is stored in chemical bonds, and the main food groups (proteins, fats and oils, and carbohydrates) have differing energy contents, measured in kJ g^{-1}.
- Photosynthesis is the process by which plants use sunlight to convert carbon dioxide and water into oxygen and organic compounds known as sugars (glucose).
- Glucose is a carbohydrate (sugar) produced during photosynthesis.
- During cellular respiration, cells break down simple organic food molecules such as glucose (through an oxidation reaction) and release the energy they contain.
- Both of these processes cycle the same molecules: carbon dioxide, oxygen, glucose, and water.
- The overall basic reactions are the reverse of each other:
  - Photosynthesis: $\text{Energy} + 6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$
  - Cellular respiration: $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l) + \text{Energy}$

1C Questions

Mild Medium Spicy

Deconstructed

Use the following diagram to answer questions 3–6.



Question 3 (1 MARK)

Photosynthesis in plants occurs when light energy is

A. reflected.

B. absorbed.

C. refracted.

D. diverted.

Question 4 (1 MARK)

Glucose can be classified as

A. an inorganic compound.

B. containing both metals and non-metals.

C. an organic compound.

D. containing inorganic elements and non-metals.

Question 5 (1 MARK)

The cellular respiration of sugars is an example of a(n)

A. oxidation reaction.

B. substitution reaction.

C. addition reaction.

D. decomposition reaction.

Question 6 (1 MARK)

Which row correctly identifies the letters in the diagram?

	I	II	III
A.	Photosynthesis	Inorganic molecules	Respiration
B.	Respiration	Organic molecules	Photosynthesis
C.	Photosynthesis	Organic molecules	Respiration
D.	Respiration	Inorganic molecules	Photosynthesis

Exam-style

Question 7 (1 MARK)

The energy content in food is expressed

A. per mole as this is most accurate.

B. per molecule due to the different food types.

C. per particle as this is most accurate.

D. per gram as it is a mixture of different types of compounds.

Question 8 (1 MARK)

Which of the following is not required for photosynthesis to occur?

A. Energy

B. Carbon dioxide

C. Water

D. Glucose

Question 9 (1 MARK)

Most algae are able to take in carbon dioxide from their surroundings and use it to make organic compounds.

This process is an example of

A. respiration.

B. photosynthesis.

C. combustion.

D. condensation.

Question 10 (4 MARKS)

Fructose, glucose, and sucrose are found naturally in fruit and some vegetables. Sugarcane and sugar beet are used to produce granulated table sugar, which contains mainly sucrose and has the formula $C_{12}H_{22}O_{11}$.

a. What is the name of the process by which animal cells release the energy stored in the bonds of sugars? 1 MARK

b. Give one similarity and one difference between a molecule of sucrose and a molecule of glucose. 2 MARKS

c. Write the equation for the complete oxidation of one molecule of sucrose. 1 MARK

Key science skills

Question 11 (6 MARKS)

Consider the following statement:

'Plants can survive on their own because they make their own food, whilst animals cannot survive on their own as they need plants for survival.'

Give evidence to both agree and disagree with this statement. Justify your answer by referencing important chemical processes.

a. Agree 3 MARKS

b. Disagree 3 MARKS

FROM LESSON 12E

Questions from multiple lessons

Question 12 (8 MARKS)

Ethanol is already extensively used as a fuel for powering transportation and can be produced from crude oil or biomass. Bioethanol is commonly produced by fermenting biomass. Advocates argue that combusting bioethanol would not alter the net emissions of carbon dioxide gas even though bioethanol produces carbon dioxide when undergoing combustion.

a. Give two advantages of burning bioethanol. Explain your answers. 4 MARKS

b. Give two disadvantages of burning bioethanol. Explain your answers. 4 MARKS

FROM LESSONS 1A & 1B

1D Enthalpy changes and combustion reactions

STUDY DESIGN DOT POINTS

- comparison of exothermic and endothermic reactions, with reference to bond making and bond breaking, including enthalpy changes (ΔH) measured in kJ, molar enthalpy changes measured in kJ mol^{-1} and enthalpy changes for mixtures measured in kJ g^{-1}, and their representations in energy profile diagrams
- combustion (complete and incomplete) reactions of fuels as exothermic reactions: the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of organic molecules using experimental data and data tables
- determination of limiting reactants or reagents in chemical reactions

1A 1B 1C 1D

- 3.1.6.1 Exothermic and endothermic reactions
- 3.1.8.1 Types of combustion reactions
- 3.1.8.2 & 3.1.8.3 Energy changes during combustion & thermochemical equations
- 3.1.7.1 Limiting reagents and reactants

ESSENTIAL PRIOR KNOWLEDGE

- Electrostatic attraction
- Bonding
- Stoichiometry

See questions 7–9.



Image: Four Oaks/Shutterstock.com

Why do some fuels release black carbon when burnt?

Black carbon is one of the largest contributors to climate change (second only to CO_2) and has disastrous impacts on human respiratory and cardiovascular health. Its increasing concentration in our atmosphere is one of the reasons scientists are searching for greener energy alternatives that can be implemented on a global scale. In this lesson, we will cover energy changes during chemical reactions, as well as different types of **combustion** reactions.

KEY TERMS AND DEFINITIONS

Activation energy (E_a) minimum amount of energy required for a reaction to proceed

Chemical energy energy stored in the bonds (electrostatic attractions) of chemical compounds

Combustion exothermic reaction between a fuel and oxygen gas

Complete combustion combustion reaction where oxygen gas is in excess, producing only carbon dioxide gas and water

Endothermic reaction chemical reaction that absorbs energy (in the form of heat) from the surrounding environment

Energy profile diagram diagram that represents energy changes during a chemical reaction

Enthalpy change (ΔH) overall change in the chemical energy of a system

Exothermic reaction chemical reaction accompanied by the release of energy (in the form of heat)

Heat of combustion amount of heat released by the complete combustion of a substance

Incomplete combustion combustion reaction where oxygen supply is limited; able to produce a range of carbon-based products in addition to water

Molar heat of combustion amount of heat, in kJ mol^{-1}, released when 1 mole of substance completely combusts in excess oxygen gas

Thermochemical equation balanced chemical equation that includes the enthalpy change (ΔH) of the reaction, measured in kJ mol^{-1} or kJ

Exothermic and endothermic reactions 3.1.6.1

Some chemical reactions, known as **exothermic** and **endothermic reactions**, release or absorb energy. To understand these properties, it is important to know and be able to show how chemical reactions transform bond energy into heat energy.

How can we represent energy changes during exothermic and endothermic reactions?

All substances contain **chemical energy** (the energy stored in the bonds of compounds), which can be released and absorbed during chemical reactions from the breaking and formation of new chemical bonds. In VCE chemistry, the main focus is describing an **enthalpy change (*ΔH*)**, which represents the total change in chemical energy during a reaction.

The enthalpy of a substance is measured in units of kJ, the molar enthalpy of a pure sample of a chemical compound is measured in kJ mol^{-1}, and the enthalpy of a mixture of chemical compounds is measured in kJ g^{-1}.

The enthalpy of a mixture of chemical compounds cannot be measured in kJ mol^{-1} because its molar mass cannot be determined, meaning an amount in moles cannot be calculated. Instead, we use units of kJ g^{-1}.

During a chemical reaction, energy is absorbed to break chemical bonds in the reactants and is released as new bonds are formed in the products. For a reaction to occur, a minimum initial amount of chemical energy is required to break the chemical bonds in the reactants, known as the **activation energy (E_a)** (figure 1).

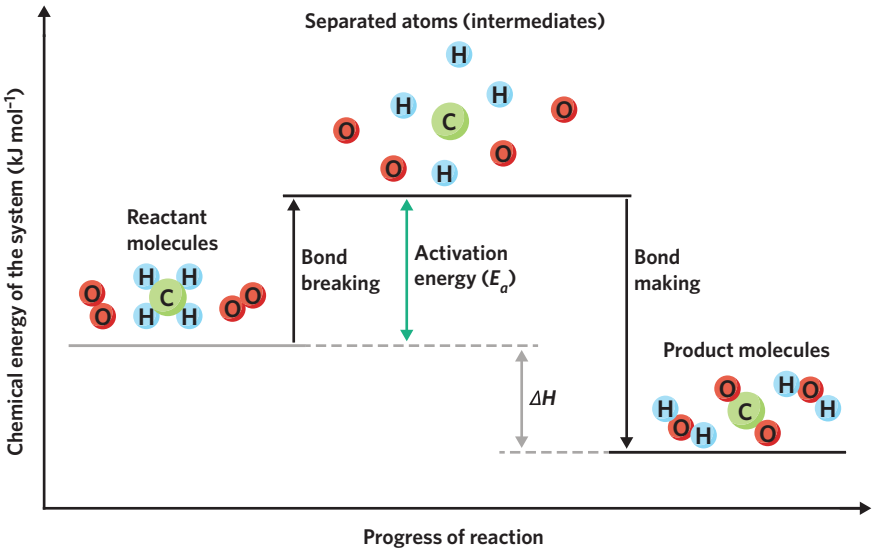


Figure 1 Energy changes during the complete combustion of methane in terms of bond breaking and bond making

During an exothermic reaction, more energy is released by the system through the creation of chemical bonds as products are formed than is absorbed to break chemical bonds in the reactants. Therefore, there is an overall decrease in enthalpy. However, during an endothermic reaction, more energy is absorbed by the system than is released. In this case, there is an overall increase in enthalpy.

USEFUL TIP

You may see the *ΔH* of a combustion reaction (without a sign) referred to as the '**heat of combustion**': the amount of energy released in a combustion reaction. **Molar heat of combustion** values (kJ mol^{-1}) for common fuels at Standard Laboratory Conditions (SLC) can be found in the VCE Data Book. These values can be determined experimentally through methods covered in later lessons.

MISCONCEPTION

'An endothermic reaction gets hotter if it absorbs energy from the surroundings.'

Absorbing heat energy is just a measurement of the energy moving into the system. Heat can move into the system without changing its temperature.

USEFUL TIP

Energy profile diagrams will not always show a horizontal axis and can have many different labels on the vertical axis.

These enthalpy changes in exothermic and endothermic reactions can be represented through **energy profile diagrams**. To interpret these, we can think of the overall increase in energy during an endothermic reaction as a 'step up' and the overall release of energy during an exothermic reaction as a 'step down' (figure 2). Energy profile diagrams will not always show a horizontal axis and can have many different labels on the vertical axis.

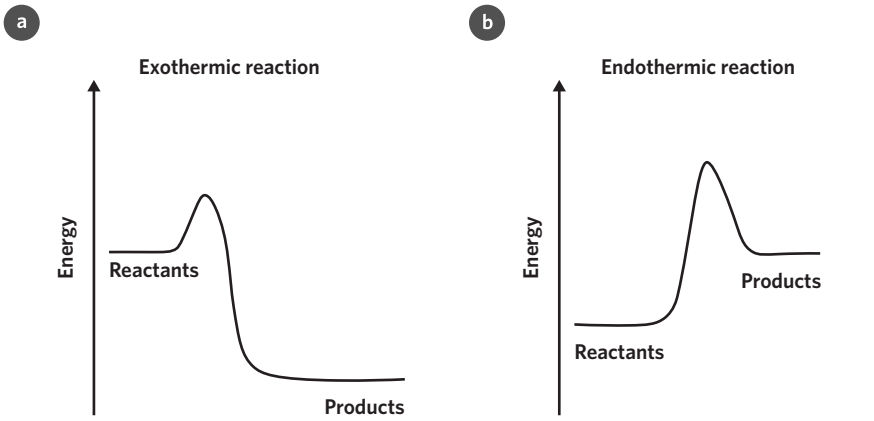


Figure 2 Shape of energy profile diagrams of **(a)** exothermic reactions (step down) and **(b)** endothermic reactions (step up)

Energy profile diagrams can also provide information about the change in enthalpy (ΔH) of the system during a chemical reaction as well as the activation energy (E_a) of the reaction, as shown in figure 3. We can think of ΔH in terms of the following equation:

ΔH = enthalpy of products − enthalpy of reactants

This means that ΔH will have a negative (−) value for exothermic reactions, and a positive (+) value for endothermic reactions.

USEFUL TIP

The prefix 'exo' means 'out' and the prefix 'endo' means 'in'. This means we can think of exothermic reactions as giving out energy to the surroundings, and endothermic reactions as taking in energy from the surroundings.

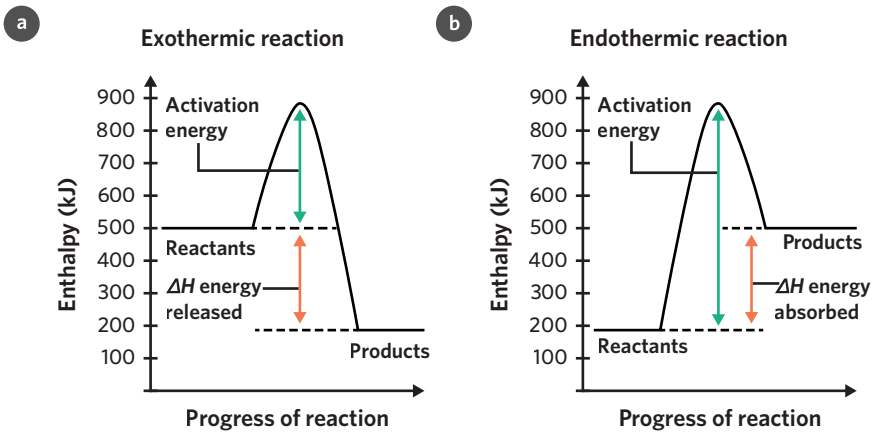


Figure 3 Detailed energy profile diagrams of **(a)** exothermic reactions (step down) and **(b)** endothermic reactions (step up)

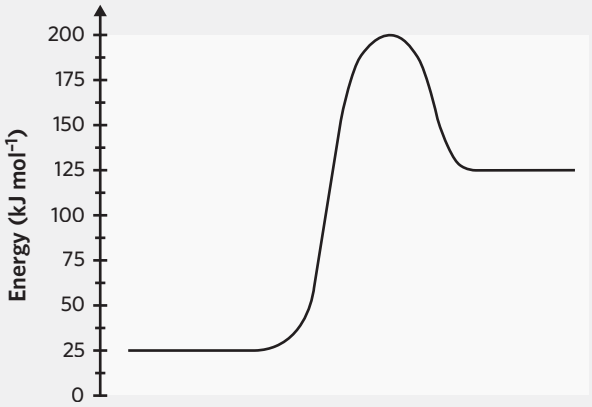
STRATEGY

Always include a + or − sign when writing ΔH values, even if they are positive.

If an energy profile diagram shows the change in enthalpy (ΔH) and activation energy (E_a) of a reaction, these values can also be determined for the reverse reaction by reading the curve from right to left. The enthalpy change of the reverse reaction will be the same size as the enthalpy change of the forward reaction. However, it must be written with the opposite sign (+ or −) because energy is absorbed in one reaction and released in the other. Note that activation energies of the forward and reverse reactions will be different and will always be larger values in the endothermic reaction, as shown in figure 3.

WORKED EXAMPLE 1

Calculate the energy required to break the bonds of the reactants and the net enthalpy change of the forward reaction in kJ mol^{-1}.



What information is presented in the question?

The energy profile diagram representing a chemical reaction.

What is the question asking us to do?

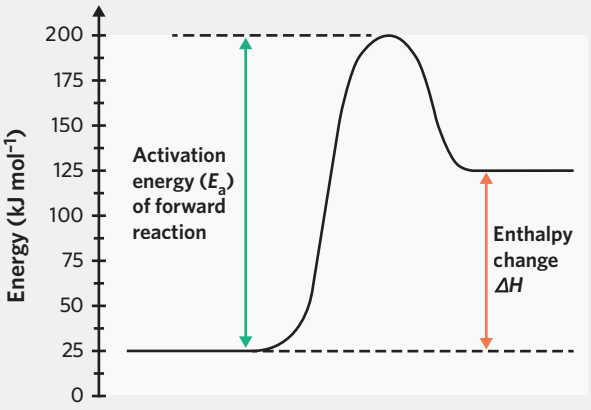
Determine the activation energy and enthalpy change of the forward reaction in kJ mol^{-1}.

What strategies do we need in order to answer the question?

1. The word 'net' has the same meaning as 'overall' or 'total'. Although the word 'total' is used most often in VCAA exams to describe a quantity of energy, you will likely come across each of these terms in questions.
2. Read the energy profile diagram forwards (from left to right) to obtain information about the forward reaction.
3. Annotate the energy profile diagram to determine how to calculate the activation energy and enthalpy change.
4. Calculate the activation energy and enthalpy change by finding the difference between energy values.
5. Always include a sign (+ or −) in front of ΔH values, even if they are positive.

Answer

The energy required to break the chemical bonds of the reactants (activation energy) is the difference between the maximum energy value reached by the system and the energy of the reactants. If we read the curve from left to right, given the question asks about the forward reaction, we can annotate the diagram to determine the energy quantities we need to calculate, as shown.



Now we can calculate these quantities by finding the difference between relevant energy values.

E_a = maximum energy value of the peak − initial energy of reactants

$E_a = +200 \text{ kJ mol}^{-1} - 25 \text{ kJ mol}^{-1}$

$E_a = +175 \text{ kJ mol}^{-1}$

and

ΔH = final energy of products − initial energy of reactants

$\Delta H = +125 \text{ kJ mol}^{-1} - 25 \text{ kJ mol}^{-1}$

$\Delta H = +100 \text{ kJ mol}^{-1}$

Finally, we have to make sure that the activation energy is a positive value and that our ΔH value is written with the appropriate sign. Looking at the shape of the curve, the forward reaction 'steps up', meaning that there is a net absorption of energy during the reaction, so the reaction is endothermic. This means the ΔH value must be written with a (+) sign.

So, $E_a = +175 \text{ kJ mol}^{-1}$ and $\Delta H = +100 \text{ kJ mol}^{-1}$.

PROGRESS QUESTIONS

Question 1

A reaction is endothermic if

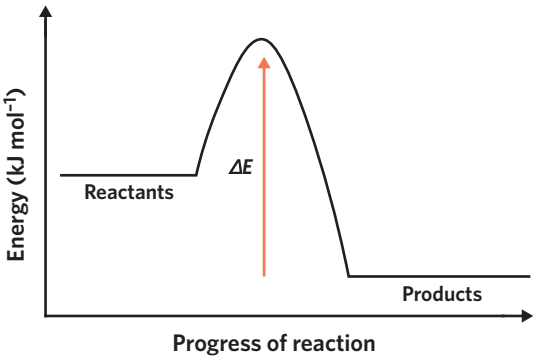
A. energy is released during the reaction.

B. energy is absorbed during the reaction.

C. energy does not change during the reaction.

D. None of the above

Question 2



The change in energy labelled ΔE in the energy profile diagram is

A. the energy required to initiate the forward reaction.

B. the activation energy for the forward reaction.

C. the enthalpy of the reaction.

D. the activation energy for the reverse reaction.

Types of combustion reactions 3.1.8.1

Different types of combustion reactions can occur depending on the amount of oxygen available to react.

How can we identify complete and incomplete combustion reactions?

Combustion reactions are a type of chemical reaction between a substance (usually a fuel) and oxygen. This means that whenever something burns in air, like a match or a candle, a combustion reaction is involved. Combustion reactions are always exothermic because there is a net release of energy during these reactions, and this energy is often released as heat. They are also a type of oxidation reaction, which will be covered in greater detail in lesson 3A.

There are two types of combustion reactions that occur depending on the supply of oxygen. If oxygen is in excess, **complete combustion** will occur. If there is a limited supply of oxygen, **incomplete combustion** will occur. Complete combustion results in the production of only carbon dioxide (CO_2) and water (H_2O). However, if other carbon-based products have formed in addition to water, incomplete combustion has occurred. These products can include carbon monoxide gas[1] (CO), carbon dioxide gas (CO_2), and solid carbon[2] (C), also known as soot. Some examples of complete and incomplete combustion reactions are shown in table 1.

KEEN TO INVESTIGATE?

[1] **Why do we put carbon monoxide detectors in our homes?**
Search: Carbon Monoxide vs Carbon Dioxide: Let's compare

KEEN TO INVESTIGATE?

[2] **What is black carbon and why is it a danger to us and our environment?**
Search: Black carbon research and future strategies

Table 1 Some possible combustion reactions of methane gas and liquid octane

Equation type	Reactants	→	Products	Type of combustion reaction
Word equation	Methane gas + Oxygen gas	→	Carbon dioxide gas + Liquid water	Complete
Unbalanced symbol equation	$CH_4(g) + O_2(g)$	→	$CO_2(g) + H_2O(l)$	
Balanced equation	$CH_4(g) + 2O_2(g)$	→	$CO_2(g) + 2H_2O(l)$	
Word equation	Methane gas + Oxygen gas	→	Carbon monoxide gas + Liquid water	Incomplete
Unbalanced symbol equation	$CH_4(g) + O_2(g)$	→	$CO(g) + H_2O(l)$	
Balanced equation	$CH_4(g) + \frac{3}{2}O_2(g)$	→	$CO(g) + 2H_2O(l)$	
Word equation	Liquid octane + Oxygen gas	→	Carbon dioxide gas + Water	Complete
Unbalanced symbol equation	$C_8H_{18}(l) + O_2(g)$	→	$CO_2(g) + H_2O(l)$	
Balanced equation	$C_8H_{18}(l) + \frac{25}{2}O_2(g)$	→	$8CO_2(g) + 9H_2O(l)$	
Word equation	Liquid octane + Oxygen gas	→	Carbon monoxide gas + Carbon dioxide gas + Solid carbon + Liquid water	Incomplete
Unbalanced symbol equation	$C_8H_{18}(l) + O_2(g)$	→	$CO(g) + CO_2(g) + C(s) + H_2O(l)$	
Balanced equation	$C_8H_{18}(l) + 9O_2(g)$	→	$CO(g) + 4CO_2(g) + 3C(s) + 9H_2O(l)$	
Another balanced equation	$2C_8H_{18}(l) + 19O_2(g)$	→	$4CO(g) + 8CO_2(g) + 4C(s) + 18H_2O(l)$	

Since fewer chemical bonds are made in the formation of products of incomplete combustion, these reactions produce less energy than complete combustion reactions of the same fuel. For example, a particular incomplete combustion reaction of one mole of pure methane gas at SLC may release up to approximately 595 kJ mol^{-1} of energy, whereas the complete combustion of one mole of pure methane gas at SLC can produce up to 890 kJ mol^{-1} of energy.

USEFUL TIP

Fractions with two as the denominator (e.g $\frac{3}{2}$) or halves (e.g $\frac{1}{2}$) can be written in front of O_2 molecules in chemical equations. This allows equations to always have 1 mole of the fuel, meaning the units will be kJ mol^{-1}. Note: these values only apply to complete combustion reactions under SLC.

USEFUL TIP

In VCE chemistry, exam questions will often specify some or all of the products of an incomplete combustion reaction to reduce the number of possible correct answers.

USEFUL TIP

As molar heats of combustion (kJ mol^{-1}) are measured at SLC, water has (l) as its state symbol. VCAA also awards marks to combustion equations written with waterin a gaseous state.

WORKED EXAMPLE 2

What is the balanced chemical equation for the combustion of ethanol in an excess of oxygen gas?

What information is presented in the question?

Ethanol is being combusted.

There is an excess supply of oxygen (this means complete combustion occurs).

What is the question asking us to do?

Write the balanced chemical equation for the complete combustion of ethanol.

Continues →

What strategies do we need in order to answer the question?

1. Write out the reactants (including states).
2. Write out the products (including states).
3. Balance the carbon atoms, hydrogen atoms, and then all of the oxygen atoms (which are also found in ethanol).

Answer

$CH_3CH_2OH(l) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$
is the unbalanced chemical reaction for the complete combustion of ethanol.

Balance the carbon atoms first:
$CH_3CH_2OH(l) + O_2(g) \rightarrow 2CO_2(g) + H_2O(l)$

Balance the hydrogen atoms next:
$CH_3CH_2OH(l) + O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

Balance the oxygen atoms next:
$CH_3CH_2OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

This is the balanced complete combustion reaction of ethanol.

WORKED EXAMPLE 3

What is a balanced chemical equation for the combustion of methanol in a limited supply of oxygen? Assume carbon monoxide and carbon (soot) are the only carbon-based products.

What information is presented in the question?

Methanol is being combusted.

There is a limited supply of oxygen (this means incomplete combustion).

The products will be carbon monoxide, solid carbon (soot), and water.

What is the question asking us to do?

Write a balanced chemical equation for the incomplete combustion of methanol, where CO and C are the only carbon-based products.

What strategies do we need in order to answer the question?

1. Write out the reactants (including states).
2. Write out the products (including states).
3. Balance the carbon atoms, hydrogen atoms, and then oxygen atoms.

Answer

$CH_3OH(l) + O_2(g) \rightarrow CO(g) + C(s) + H_2O(l)$

This is an unbalanced chemical equation for the incomplete combustion of methanol.

Balance the carbon atoms first:
$2CH_3OH(l) + O_2(g) \rightarrow CO(g) + C(s) + H_2O(l)$

Balance the hydrogen atoms next:
$2CH_3OH(l) + O_2(g) \rightarrow CO(g) + C(s) + 4H_2O(l)$

Balance the oxygen atoms next:
$2CH_3OH(l) + \frac{3}{2}O_2(g) \rightarrow CO(g) + C(s) + 4H_2O(l)$

or $4CH_3OH(l) + 3O_2(g) \rightarrow 2CO(g) + 2C(s) + 8H_2O(l)$

This is one of many possible balanced equations for this reaction.

PROGRESS QUESTIONS

Question 3

What type of reaction is represented by the following equation?

$4CH_4(g) + 7O_2(g) \rightarrow 2CO_2(g) + 2CO(g) + 8H_2O(l)$

A. Complete combustion reaction

B. Semi-complete combustion reaction

C. Incomplete combustion reaction

D. None of the above

Question 4

The sign of the enthalpy change of a combustion reaction is

A. negative because exothermic reactions have a negative enthalpy change value.

B. positive because exothermic reactions have a positive enthalpy change value.

C. negative because endothermic reactions have a negative enthalpy change value.

D. positive because endothermic reactions have a positive enthalpy change value.

Question 5

Which of the following reactions represents a balanced equation for the incomplete combustion of ibuprofen $C_{13}H_{18}O_2(s)$?

A. $C_{13}H_{18}O_2(s) + 9O_2(g) \rightarrow 13CO(g) + 9H_2O(l)$

B. $C_{13}H_{18}O_2(s) + 9O_2(g) \rightarrow 13CO_2(g) + 9H_2O(l)$

C. $C_{13}H_{18}O_2(s) + 10O_2(g) \rightarrow 13CO(g) + 9H_2O(l)$

D. $C_{13}H_{18}O_2(s) + 10O_2(g) \rightarrow 13CO_2(g) + 9H_2O(l)$

Energy changes during combustion & thermochemical equations 3.1.8.2 & 3.1.8.3

The exothermic properties of combustion reactions can be harnessed to produce energy and power our world. **Thermochemical equations** are a useful tool to show the overall energy change in exothermic and endothermic reactions, including combustion reactions.

How can we show energy changes during chemical reactions?

To show energy changes during an exothermic or endothermic reaction, we can write a thermochemical equation. In a thermochemical equation, we write the balanced chemical equation, including the states, and to the right of the equation we include the enthalpy change (ΔH) in units of kJ or kJ mol^{-1} to signify the amount of energy that is lost or gained by the system.

A ΔH value written in kJ mol^{-1} refers to the enthalpy change per 1 mole of a fuel combusted. For example, the equation below shows the complete combustion of 1 mole of methanol.

$CH_3OH(l) + \frac{3}{2}O_2(g) \rightarrow CO_2(g) + 2H_2O(l) \quad \Delta H = -726 \text{ kJ mol}^{-1}$

MISCONCEPTION

'If the coefficients of the equation are doubled, the ΔH value in kJ mol^{-1} is also doubled.'

The ΔH value in kJ mol^{-1} is a fixed value, but the energy in kJ will double. In the past, if, for instance, 2 moles of a fuel was combusted, the units of kJ mol^{-1} were used and awarded marks, whereas now the units will be just kJ. This is a change for the new VCE chemistry study design.

If we were to write the equation for the reverse reaction of this example, the sign of ΔH would change, but its magnitude (size) would stay the same, as shown below.

$CO_2(g) + 2H_2O(l) \rightarrow CH_3OH(l) + \frac{3}{2}O_2(g) \quad \Delta H = +726 \text{ kJ mol}^{-1}$

A ΔH value in kJ refers to the overall enthalpy change of a chemical reaction. Here, we assume that one mole of each reagent without a coefficient is reacted. This means that if the coefficients of an equation were doubled, the ΔH value in kJ would also double. For example, consider the complete combustion of 2 moles of methanol shown in the equation below, where the molar heat of combustion of methanol is 726 kJ mol^{-1}.

$2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l) \quad \Delta H = -1452 \text{ kJ}$

As discussed above, if we were to write the equation for the reverse reaction of this example, the sign of ΔH would change, but its magnitude (size) would stay the same, as shown in the example below.

$2CO_2(g) + 4H_2O(l) \rightarrow 2CH_3OH(l) + 3O_2(g) \quad \Delta H = +1452 \text{ kJ}$

WORKED EXAMPLE 4

Ethanol reacts with oxygen according to the following equation:

$C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \quad \Delta H = -1366.8 \text{ kJ mol}^{-1}$

Calculate ΔH for the following reaction using the units kJ mol^{-1} and kJ:

$4CO_2(g) + 6H_2O(l) \rightarrow 2C_2H_5OH(l) + 6O_2(g)$

What information is presented in the question?

The equation for the combustion of ethanol and its enthalpy of combustion: $\Delta H = -1366.8$ kJ mol^{-1}.

The reaction is given in reverse, with the stoichiometric ratio doubled.

What is the question asking us to do?

Calculate ΔH for the given reaction in units of kJ mol^{-1}, and then in units of kJ.

What strategies do we need in order to answer the question?

1. Reverse the sign of ΔH as the reaction has reversed.
2. For ΔH values in kJ mol^{-1}, the size of ΔH remains the same when coefficients are changed.
3. For ΔH values in kJ, ΔH is doubled as the number of moles of the constituents are doubled.

Answer

ΔH for the second equation is positive, so must be written with a + sign.

Even though the mole amount for each of the constituents has doubled, the size of the ΔH value in units of kJ mol^{-1} remains the same.

$\Delta H = +1366.8 \text{ kJ mol}^{-1}$

In units of kJ, the mole amount of the constituents has doubled, so ΔH must also be doubled.

$\Delta H = 2 \times (+1366.8 \text{ kJ})$

$\Delta H = +2733.6 \text{ kJ}$

Therefore,

$\Delta H = +1366.8$ kJ mol^{-1} and there is an overall enthalpy change of +2733.6 kJ for the reaction.

PROGRESS QUESTIONS

Question 6

Which of the following is an example of a thermochemical equation?

A. $C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

B. $C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \quad \Delta H = -1366.8 \text{ kJ mol}^{-1}$

C. $\Delta H = -1366.8 \text{ kJ mol}^{-1}$

D. All of the above

Continues →

Question 7

Given that the heat of combustion of methanol (CH_3OH) is 726 kJ mol^{-1} at SLC, what is the value of ΔH for the following equation at SLC?

$2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$

A. $+726$ kJ mol^{-1}

B. -726 kJ mol^{-1}

C. $+1452$ kJ mol^{-1}

D. -1452 kJ mol^{-1}

Question 8

Based on the following thermochemical equation of ice melting, which equation would have a ΔH value of -18.0 kJ?

$H_2O(s) \rightarrow H_2O(l) \quad \Delta H = +6.0$ kJ mol^{-1}

A. $H_2O(l) \rightarrow H_2O(s)$

B. $3H_2O(s) \rightarrow 3H_2O(l)$

C. $3H_2O(l) \rightarrow 3H_2O(s)$

D. $H_2O(s) \rightarrow H_2O(l)$

Limiting reagents and reactants 3.1.7.1

The amount of each reactant available to react can impact both the amount of products produced, as well as the types of products that can be formed. This is a particularly important factor in determining the type of combustion reaction that will occur. Note: this section only covers gaseous reactants in combustion reactions. Limiting reagents and reactants involving solutions will be covered in lesson 9D.

How can we determine limiting and excess reagents?

To determine the products formed in a chemical reaction and their quantities, we often have to consider limiting and excess reagents. We can identify limiting and excess reagents in combustion reactions by determining whether incomplete or complete combustion has occurred.

As we have learned, complete combustion occurs when oxygen is either in sufficient supply or in excess, and incomplete combustion occurs when oxygen is the limiting reactant. Since there is enough oxygen available during complete combustion for the fuel to be completely oxidised to form CO_2, only carbon dioxide and water are formed.

USEFUL TIP

The terms 'reagent' and 'reactant' have similar definitions and are often used interchangeably. Whilst reagents are not necessarily consumed during a reaction, reactants are. A catalyst, which will be covered in lesson 4A, is an example of a reagent that is not a reactant.

However, in incomplete combustion reactions, there is insufficient oxygen supply for the fuel to be fully oxidised to CO_2. This means that in addition to water vapour, carbon monoxide and solid carbon (soot) can be produced instead of carbon dioxide. Note that carbon dioxide can also be produced during incomplete combustion reactions when either carbon monoxide or solid carbon are also products.

USEFUL TIP

During the combustion of fuels, oxygen supply being limited is the same as the fuel being in excess (and vice versa).

WORKED EXAMPLE 5

Identify the reagent(s) in the reaction below that are limiting and in excess.

$2C_6H_{14}(l) + 10O_2(g) \rightarrow 3CO_2(g) + 9C(s) + 14H_2O(l)$

What information is presented in the question?

The balanced chemical equation showing the reaction between hexane and oxygen gas to produce carbon dioxide, solid carbon, and water.

What is the question asking us to do?

Determine whether there are limiting or excess reagents in the given reaction.

Identify any limiting or excess reagents in the given reaction.

What strategies do we need in order to answer the question?

1. Complete combustion occurs when there is sufficient oxygen supply or if oxygen gas is in excess, and incomplete combustion occurs when there is a limited supply of oxygen.
2. Complete combustion reactions only produce carbon dioxide and water, whereas incomplete combustion reactions can also produce carbon monoxide and solid carbon, as well as carbon dioxide and water.
3. When there is a limiting reagent in a reaction, there will always be an excess reagent present too.

Answer

We can see that in the given equation, the products are CO_2, C, and H_2O. Solid carbon is only produced in incomplete combustion reactions, meaning there is insufficient oxygen supply in this reaction. Therefore, O_2 is the limiting reagent in this reaction and the fuel (hexane) is in excess.

KEEN TO INVESTIGATE?

[3] **How can excess oxygen create explosive conditions?**
Search YouTube: Explosion of natural gas in a tin can

When it comes to the combustion of fuels, oxygen being in excess or in limited supply can both be hazardous. Harmful particles are released into the atmosphere during incomplete combustion, whereas excess oxygen can create explosive conditions.[3]

PROGRESS QUESTIONS

Question 9

In the following reaction:

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

I. Oxygen is in excess and methane is the limiting reagent.

II. Oxygen is the limiting reagent and methane is in excess.

III. Neither reactant is in excess.

Which of the above statements is/are correct?

A. I only

B. II only

C. III only

D. Limiting and excess reagents cannot be determined.

Question 10

In the following reaction

$C_2H_6(g) + \frac{5}{2}O_2(g) \rightarrow 2CO(g) + 3H_2O(l)$

A. $O_2(g)$ is the limiting reagent.

B. $C_2H_6(g)$ is the limiting reagent.

C. $O_2(g)$ is the excess reagent.

D. $CO(g)$ is the limiting reagent.

Continues →

Question 11

In which of the following reactions has complete combustion occurred?

A. $4CH_4(g) + 7O_2(g) \rightarrow 2CO_2(g) + 2CO(g) + 8H_2O(l)$

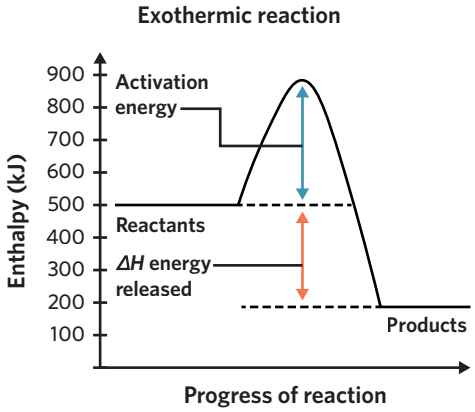
B. $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

C. $2CH_4(g) + 3O_2(g) \rightarrow 2CO(g) + 4H_2O(l)$

D. $4CH_4(g) + 5O_2(g) \rightarrow 2CO(g) + 2C(s) + 8H_2O(l)$

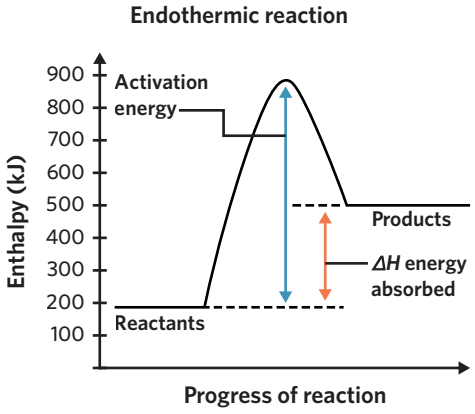
Theory summary

- Exothermic reactions:



  - Energy released as chemical bonds in the products are formed > energy absorbed to break bonds in the reactants ('step down' on energy profile diagram).
  - All combustion reactions (reaction between fuel and oxygen gas) are exothermic.

- Endothermic reactions:



  - Energy absorbed to break the chemical bonds in the reactants > energy released as bonds in the products are formed ('step up' on energy profile diagram).

- The enthalpy of a reaction of a pure substance can be written in the units:
  - kJ to represent the total energy change during a reaction.
  - kJ mol^{-1} to represent the energy change per one mole of a fuel that reacts.
  - kJ g^{-1} to represent the energy change per gram of a mixture reacted, as its molar amount cannot be determined.

- The molar heat of combustion of a fuel in kJ mol^{-1} indicates the maximum amount of energy that can be released when one mole of the fuel undergoes complete combustion.

- Thermochemical equations show the enthalpy change (ΔH) and a balanced chemical equation.
- Complete combustion occurs when there is a plentiful supply of oxygen, allowing the reaction to proceed to completion. Products of the complete combustion of fuels are carbon dioxide and water.
- Incomplete combustion occurs when there is a limited supply of oxygen. Products of the incomplete combustion of carbon-based fuels include water and at least one of the following products containing carbon:
  - carbon monoxide gas - CO(g)
  - solid carbon (black carbon or soot) - C(s).

1D Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 12–14.

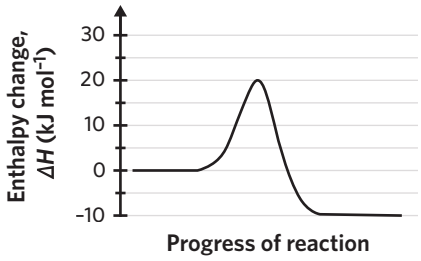
A team of scientists are investigating a chemical reaction that may be used in reusable hand warmers. The heat-releasing reaction is initiated in these hand warmers when the user bends the metal disc inside it. Then, the hand warmers can be 'reset' by being boiled for around 15 minutes and cooled before they are used again.

The reaction that takes place in these hand warmers is a reversible reaction with an activation energy, E_a, of +20 kJ mol^{-1} and an enthalpy change, ΔH, of −10 kJ mol^{-1} for the forward reaction. The reactants have an initial molar enthalpy of +10 kJ mol^{-1}.

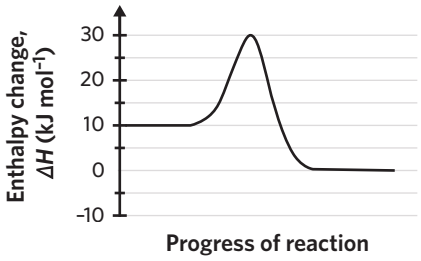
Question 12 (1 MARK)

Which is the energy profile diagram for the forward reaction?

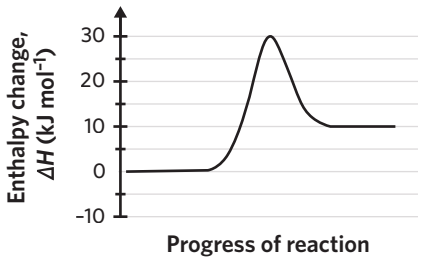
A.



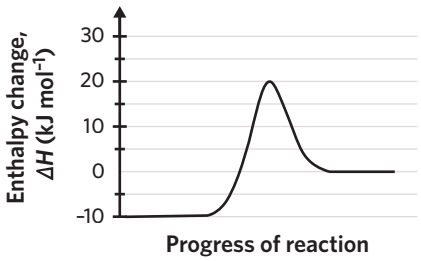
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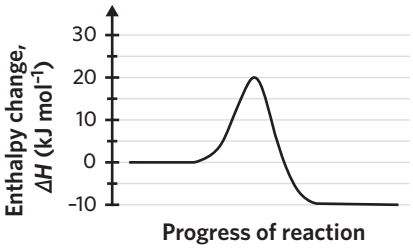


Adapted from VCAA (NHT) 2019 exam Multiple choice Q30

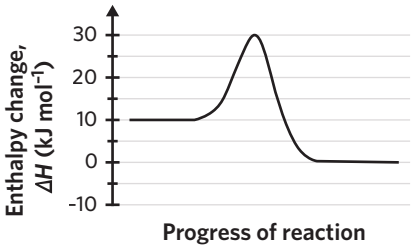
Question 13 (1 MARK)

Which is the energy profile diagram for the reverse reaction?

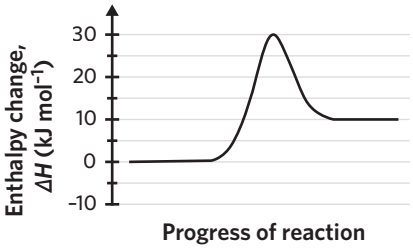
A.



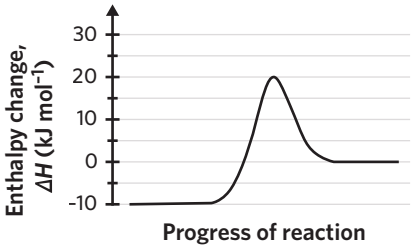
B.



C.



D.



Adapted from VCAA (NHT) 2019 exam Multiple choice Q30

Question 14 (3 MARKS)

All chemical reactions have an activation energy.

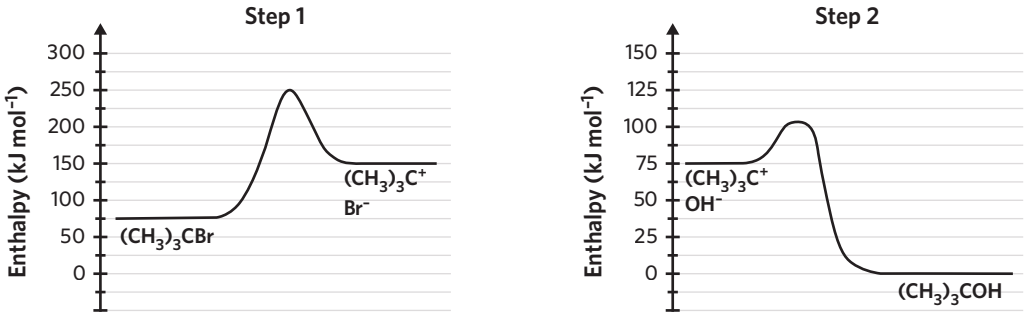
a. Calculate the activation energy, E_a, and the change in enthalpy, ΔH, of the reverse reaction. 2 MARKS

b. Why would the team of scientists want the reaction to have a relatively low activation energy? 1 MARK

Exam-style

Question 15 (4 MARKS)

The energy profile diagrams for steps 1 and 2 of a reaction are shown below.



a. Which step involves an endothermic reaction? Provide a reason for your answer. 2 MARKS

b. What is the activation energy of the reaction shown in step 1? 1 MARK

c. Calculate ΔH for the reaction represented in step 2. 1 MARK

Adapted from VCAA 2012 Exam 2 Short answer Q2bi

Question 16 (1 MARK)

In an exothermic reaction the

A. reaction system gains energy from the surroundings.

B. enthalpy of the products is greater than the enthalpy of the reactants.

C. activation energy is always greater than the enthalpy of reaction.

D. energy required to break bonds in the reactants is less than the energy released when bonds are formed in the products.

Adapted from VCAA 2011 Exam 2 Multiple choice Q6

Question 17 (1 MARK)

The reaction

$A + B \rightarrow C \quad \Delta H > 0$

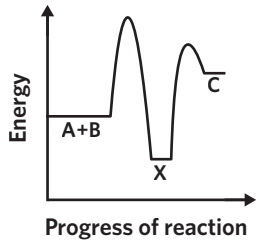
Involves a two-step process

$A + B \rightarrow X \quad \Delta H < 0$

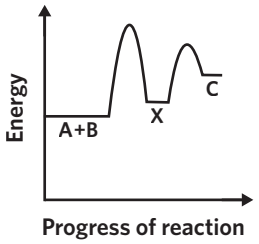
$X \rightarrow C \quad \Delta H > 0$

Which of the following diagrams best represents the energy changes during the reaction?

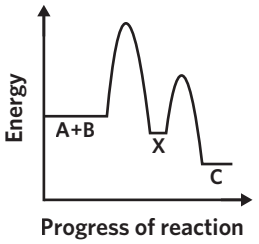
A.



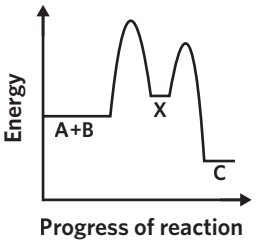
B.



C.



D.



Adapted from VCAA 2007 Exam 1 Multiple choice Q19

Question 18 (1 MARK)

In some circumstances, there is a limited supply of oxygen.

Write the balanced chemical equation for the combustion reaction of the major component of biodiesel, $C_{19}H_{32}O_2$, where carbon monoxide, CO, is the only product containing carbon.

VCAA 2017 exam Short answer Q2c

Question 19 (2 MARKS)

The combustion of butane takes place according to the equation

$$C_4H_{10}(l) + \frac{13}{2}O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$$

Consider the following reaction.

$$8CO_2(g) + 10H_2O(l) \rightarrow 2C_4H_{10}(g) + 13O_2(g)$$

What is the value of ΔH for this reaction in kJ?

Adapted from VCAA 2016 exam Multiple choice Q17

Question 20 (1 MARK)

An equation for the complete combustion of methanol is

$$2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$$

Assuming this reaction occurs under SLC, what is the value of ΔH for this reaction in kJ?

Adapted from VCAA 2018 exam Multiple choice Q14

Question 21 (5 MARKS)

Tiberius decided to burn some butane to see what the products of the reaction would be. They set up a device that could detect the presence of water and carbon dioxide. When they burnt the butane, water as vapour was present, but carbon dioxide was not.

a. Write a balanced thermochemical equation representing the complete combustion reaction of butane. 1 MARK

b. What would the lack of carbon dioxide indicate about the type of combustion reaction that occurred? 2 MARKS

c. Is the conversion of liquid water to water vapour (a process which occurred in this reaction) an endothermic or exothermic process? Justify your answer. 2 MARKS

Key science skills

Question 22 (10 MARKS)

Chemistry student Anastasiya notices that when she heats a ceramic crucible over a bunsen burner with a yellow flame (air holes closed) for 60 seconds, the bottom of the crucible becomes coated with a black substance. However, when she heats an identical crucible over a blue bunsen burner flame (air holes open) for the same amount of time, it remains clean.



Images (left to right): Choze-KL, Stefan Schierle/Shutterstock.com

a. Explain Anastasiya's observations. 4 MARKS

b. Anastasiya predicts that if she opened the air holes halfway, the crucible would still remain clean because some air will be let into the bunsen burner.

i. Suggest why someone may agree with Anastasiya's prediction. 2 MARKS

ii. Suggest why someone may disagree with Anastasiya's prediction. 2 MARKS

c. Anastasiya then heats a crucible with the air holes of the bunsen burner opened half way and constructs the following table of results based on her findings.

Bunsen burner air holes	Closed	Half open	Open
Observations	Crucible becomes covered with a dark/black coating	Crucible becomes coated with a grey coating	Crucible remains clean - no observable changes

i. What type of data has Anastasiya collected? 1 MARK

ii. What could Anastasiya measure to quantitatively determine how much coating has appeared on the crucible? 1 MARK

FROM LESSONS 12B & 12C

Questions from multiple lessons

Question 23 (2 MARKS)

A chemist is testing the amount of energy that can be obtained from a sample of biodiesel under certain conditions. At 298 K, the biodiesel is found to have a heat of combustion of 37 kJ g^{-1}.

a. Why is the molar enthalpy of biodiesel unable to be determined? 1 MARK

b. What would the overall enthalpy change during the reaction be if 200 g of the fuel was completely combusted at 298 K? Give your answer in kJ. 1 MARK

FROM LESSON 1B

Question 24 (3 MARKS)

On a cold and rainy day, a propane LPG heater was used to heat a small, enclosed, outdoor area. The fuel in this heater is sourced from fossil fuels.

a. Write a balanced chemical equation for the incomplete combustion of propane gas, where carbon monoxide and soot are the only products containing carbon. 1 MARK

Adapted from VCAA (NHT) 2021 exam Short answer Q2a

b. Is this fuel carbon neutral? Explain your answer. 2 MARKS

FROM LESSON 1A

Chapter 1 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which one of the following fuels is the most sustainable?

A. Coal

B. Ethanol

C. Natural gas

D. Coal seam gas

Question 2 (1 MARK)

Which one of the following statements about fuels is correct?

A. Petrol is a form of renewable energy.

B. Electricity can only be generated by burning coal.

C. Carbon dioxide is not produced when biogas is burned.

D. Biodiesel can be derived from both plant and animal material.

VCAA 2018 exam Multiple choice Q3

Question 3 (1 MARK)

Which one of the following statements indicates why ethanol produced from sugarcane is defined as a biofuel and ethanol produced from coal is not?

A. Ethanol produced from sugar cane generates less greenhouse gases when used as a fuel than ethanol produced from coal.

B. Ethanol produced from coal can be used to generate electrical energy whereas ethanol produced from sugar cane cannot.

C. Sugar cane is recently living organic matter whereas coal is formed over millions of years.

D. Sugar cane is a natural resource whereas coal is not.

VCAA (NHT) 2019 exam Multiple choice Q7

Question 4 (1 MARK)

Which of the following molecular formulas is most likely to be that of biodiesel?

A. $C_4H_8O_2$

B. $C_{17}H_{34}O_2$

C. C_8H_{18}

D. $C_{17}H_{36}$

Question 5 (1 MARK)

Common food groups include: carbohydrates, fats, oils, and proteins.
Which of these food groups is least likely to be used as an energy source in the human body?

A. Carbohydrates

B. Fats

C. Oils

D. Proteins

Question 6 (1 MARK)

Biodiesel can be obtained via

A. addition of methanol to triglycerides from organic matter.

B. transesterification of triglycerides from fossilised remains.

C. fractional distillation of crude oil.

D. oxidation of fatty acid methyl esters.

Question 7 (1 MARK)

Which of the following is most likely to cause a sudden decrease in the rate of photosynthesis?

A reduction in the availability of

A. oxygen.

B. hydrogen.

C. carbon dioxide.

D. carbon monoxide.

Question 8 (1 MARK)

Which of the following reactions represents a balanced equation where oxygen gas is the limiting reactant?

A. $C_{13}H_{18}O_2(s) + 5\frac{1}{2}O_2(g) \rightarrow 13CO(g) + 9H_2O(l)$

B. $C_{13}H_{18}O_2(s) + 17\frac{1}{2}O_2(g) \rightarrow 13CO_2(g) + 9H_2O(l)$

C. $C_{13}H_{18}O_2(s) + 10O_2(g) \rightarrow 13CO(g) + 9H_2O(l)$

D. $C_{13}H_{18}O_2(s) + 33O_2(g) \rightarrow 13CO_2(g) + 9H_2O(l)$

Question 9 (1 MARK)

Given the following reaction

$4CO_2(g) + 6H_2O(l) \rightarrow 2C_2H_5OH(g) + 6O_2(g) \quad \Delta H = +2728 \text{ kJ}$

We would expect the ΔH value for the following reaction to be:

$C_2H_5OH(g) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

A. $+1364 \text{ kJ mol}^{-1}$

B. $-1364 \text{ kJ mol}^{-1}$

C. $+5456 \text{ kJ mol}^{-1}$

D. $-5456 \text{ kJ mol}^{-1}$

Question 10 (1 MARK)

Consider the following set of balanced thermochemical equations.

$2NO_2(g) \rightarrow 2NO(g) + O_2(g) \qquad \Delta H = +14 \text{ kJ}$

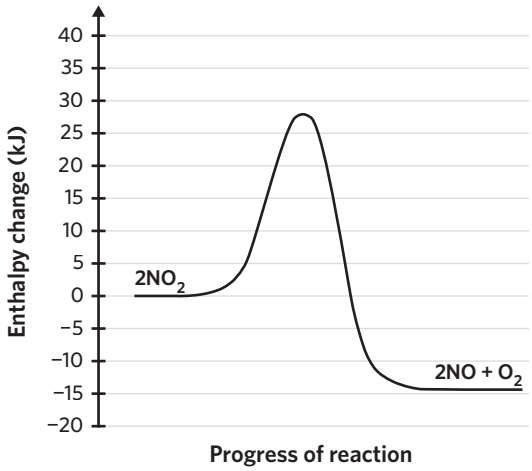
$NO_2(g) + CO(g) \rightarrow CO_2(g) + NO(g) \qquad \Delta H = -226 \text{ kJ}$

$2NO_2(g) \rightleftharpoons N_2O_4(g) \qquad \Delta H = -57 \text{ kJ}$

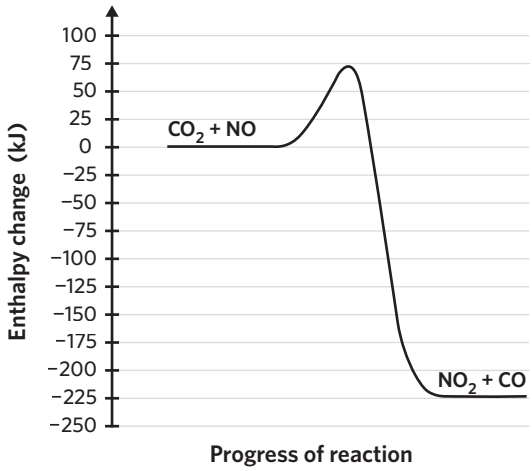
$N_2(g) + O_2(g) \rightleftharpoons 2NO(g) \qquad \Delta H = +181 \text{ kJ}$

Which one of the following graphs is consistent with the chemical equations shown?

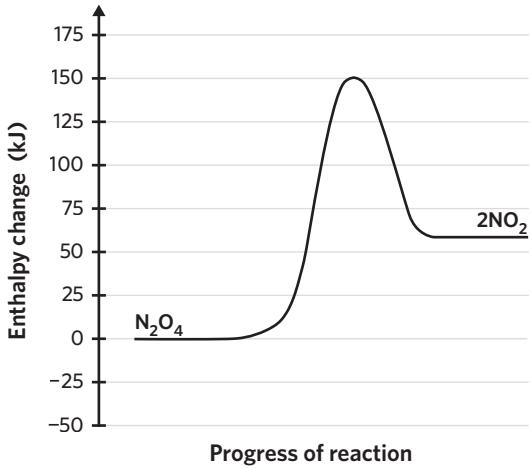
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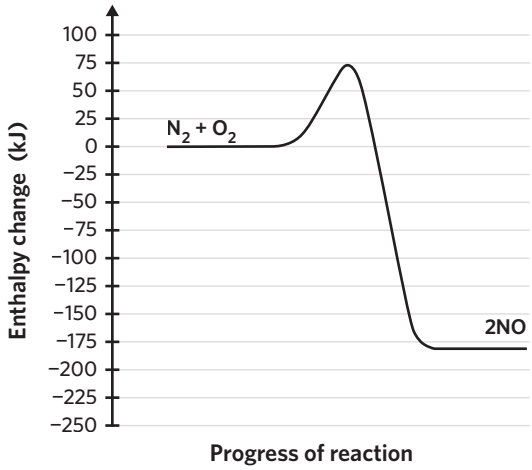
B.



C.



D.



Adapted from VCAA 2021 exam Multiple choice Q18

Short answer (30 MARKS)

Question 11 (6 MARKS)

Different types of fuels can be used in vehicles with combustion engines. These fuels can be produced from either fossil fuels or from renewable sources. Liquefied petroleum gas (LPG), a fossil fuel used in cars, is mainly made up of propane, C_3H_8.

a. Write a balanced thermochemical equation (including states) for the complete combustion of C_3H_8 in air at standard laboratory conditions (SLC). 3 MARKS

b. Write a possible balanced equation (including states) for the incomplete combustion of C_3H_8 in air at standard laboratory conditions (SLC), where only one of the products contains carbon. 2 MARKS

c. Predict, giving a reason, whether the enthalpy change in part **b** will be larger than, smaller than, or equal to the value for part **a**. 1 MARK

Question 12 (7 MARKS)

A global ethanol production company is investigating a potential new source for their fuel. Currently, this company sources ethanol from coal deposits underground, but researchers have proposed the use of sweet potatoes as an alternative source. Sweet potatoes are harvested from crops and fermented by bacteria, which produces ethanol.

a. Explain why ethanol sourced from coal is considered non-renewable, whereas ethanol sourced from sweet potatoes is considered renewable. 2 MARKS

b. The researchers of the company are interested in the specific process of the fermentation of sweet potatoes. Give the chemical equation for the fermentation reaction. 2 MARKS

c. Describe one environmental advantage, with respect to the production of carbon dioxide, of switching to the use of sweet potatoes as an energy source as opposed to coal deposits. 2 MARKS

d. Identify one negative impact that the growth of sweet potato crops may have on the environment. 1 MARK

Question 13 (8 MARKS)

One process of extracting petrol from the environment is summarised below.



a. Would the product of this process be considered a renewable or non-renewable fuel? Justify your answer. 2 MARKS

b. A sample of petrol is extracted and analysed. What intermolecular force(s) would you expect to observe in this sample? Use the structure of petrol in your explanation. 2 MARKS

c. Through an error in the transport of the crude oil from the drilling facility to the refinery, the sample of petrol was actually contaminated with biodiesel to a large extent. Would this contamination lead to a higher or lower boiling point compared to a pure sample of petrol? Explain your reasoning. 3 MARKS

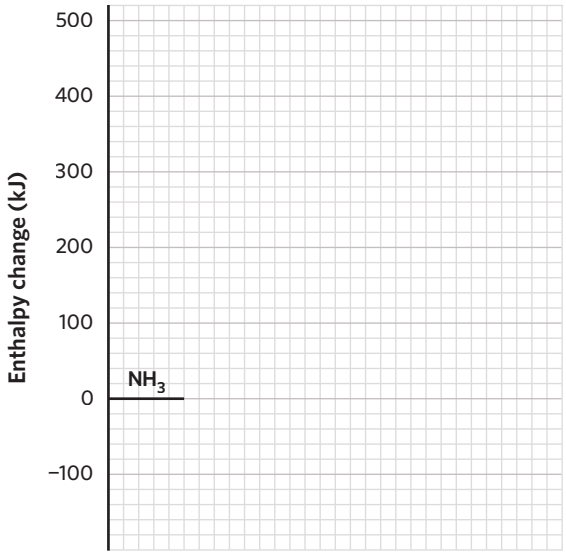
d. The pure product petrol is now combusted in a vehicle's engine to harness its energy. Identify one negative effect of this combustion reaction on the environment. 1 MARK

Question 14 (3 MARKS)

The decomposition of ammonia is represented by the following equation.

$2NH_3(g) \rightleftharpoons N_2(g) + 3H_2(g) \quad \Delta H = +92.4$ kJ

The activation energy for the uncatalysed reaction is +335 kJ.
The activation energy for the reaction when tungsten is used as a catalyst is +163 kJ.
On a grid similar to the one provided, draw a labelled energy profile diagram for the uncatalysed and catalysed reactions.



Adapted from VCAA 2014 exam Short answer Q1a

Question 15 (6 MARKS)

Year 12 chemistry students Ruchika and Katrina each attain their probationary licences and begin researching options for the purchase of their first cars. Both students are looking for a renewable energy source to fuel their car. Ruchika is interested in an electric car, whereas Katrina is looking for a car fuelled by bioethanol.

a. Ruchika proposes that their car would be running on a sustainable energy source because the electricity used to power the car is generated from the combustion of natural gas. Comment on the accuracy of this statement. 2 MARKS

b. Katrina hires an expert to investigate the fuel efficiency of a range of models she is interested in. The results of this investigation are summarised below.

	Car 1	Car 2	Car 3	Car 4
Fuel efficiency (L/100 km)	21.3	17.6	17.3	11.4
CO_2 produced (g (CO_2)/L)	1750	2479	2453	2871

If the journey to the ski lodge is 75 km, which car would produce the least amount of CO_2 for this trip? 2 MARKS

c. Katrina is looking to compare bioethanol and petrol and finds that bioethanol produces 1.91 kg of CO_2 per kg of fuel, compared with 3.17 kg of CO_2 per kg for petrol. However, the overall impact of the carbon dioxide released by bioethanol is significantly lower than that of petrol. Explain this result with reference to the origin of bioethanol. 2 MARKS

Key science skills (10 MARKS)

Question 16 (6 MARKS)

Jules, an automobile safety engineer tasked with testing an engine's capacity to combust different fuels, conducts the following experiment to investigate the boiling point of a range of different molecules. The engineer is supplied with a large supply of petrol, biodiesel, and bioethanol with which to perform the experiment. In a controlled environment, 100 g samples of each fuel were heated until vapourised, and their respective boiling points were recorded with a digital thermometer.

a. Name the independent and dependent variables in this experiment. 2 MARKS

b. The experimentally determined values of the boiling points for each of the fuels were, in increasing order:

Ethanol 78 °C

Petrol 250 °C

Biodiesel 360 °C

Jules notes that the boiling point for petrol, which they know is a non-polar hydrocarbon, is found to be higher than the boiling point of ethanol, which they know is a highly polar molecule. If, in fact, Jules' experimental results are accurate, suggest a reason why petrol has a higher boiling point than ethanol. 2 MARKS

c. If the engineer only has access to the resources mentioned above, identify a method to improve the precision of their results. Explain your answer. 2 MARKS

FROM LESSONS 12A & 12D

Question 17 (4 MARKS)

Produce a short overview focusing on both the similarities and differences between cellular respiration and photosynthesis. Limit your response to a maximum of 75 words. Dot points are acceptable.

FROM LESSON 12E

Back to contents

2

CHAPTER 2

Measuring changes in chemical reactions

LESSONS

2A Calculating energy changes from combustion reactions

2B Calculating energy changes using water

2C Energy from fuels and food

Chapter 2 review

KEY KNOWLEDGE

- calculations related to the application of stoichiometry to reactions involving the combustion of fuels, including mass-mass, mass-volume and volume-volume stoichiometry, to determine heat energy released, reactant and product amounts and net volume or mass of major greenhouse gases (CO_2, CH_4 and H_2O), limited to standard laboratory conditions (SLC) at 25 °C and 100 kPa
- the use of specific heat capacity of water to approximate the quantity of heat energy released during the combustion of a known mass of fuel and food
- the principles of solution calorimetry, including determination of calibration factor and consideration of the effects of heat loss; analysis of temperature-time graphs obtained from solution calorimetry
- energy from fuels and food:
  - calculation of energy transformation efficiency during combustion as a percentage of chemical energy converted to useful energy
  - comparison and calculations of energy values of foods containing carbohydrates, proteins and fats and oils

Image: Pongsathon Ladasuwankul/Shutterstock.com

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2A Calculating energy changes from combustion

STUDY DESIGN DOT POINT

- calculations related to the application of stoichiometry to reactions involving the combustion of fuels, including mass-mass, mass-volume and volume-volume stoichiometry, to determine heat energy released, reactant and product amounts and net volume or mass of major greenhouse gases (CO_2, CH_4 and H_2O), limited to standard laboratory conditions (SLC) at 25 °C and 100 kPa

2A 2B 2C

- 3.1.9.1 Mass to mass calculations involving combustion
- 3.1.9.2 Mass to volume calculations involving combustion
- 3.1.9.3 Volume to volume calculations involving combustion
- 3.1.9.4 Enthalpy changes

ESSENTIAL PRIOR KNOWLEDGE

- Stoichiometric ratios
- Ideal gas behaviour
- 1D Thermochemical equations

See questions 10–12.



Image: Gorloff-KV/Shutterstock.com

Is LPG the best fuel to use in cars?

LPG (liquefied petroleum gas) is a propane-based transport fuel that was once popular in Australia due to its lower emissions, but has since declined in usage. As well as emissions, factors such as cost, energy content, and practical considerations are often taken into account when comparing transport fuels. In this lesson, we will explore how to calculate, for the combustion of fuels, the amounts of: energy released, products produced, **greenhouse gases** emitted, and reactants required.

KEY TERMS AND DEFINITIONS

Greenhouse gases gases that contribute to the enhanced greenhouse effect by absorbing and emitting infrared radiation from the sun

Molar heat of combustion amount of heat, in kJ mol^{-1}, released when 1 mole of substance completely combusts in excess oxygen gas

Molar volume of gases (V_m) volume occupied by one mole of an ideal gas at a given temperature and pressure

Standard laboratory conditions (SLC) set of conditions used as a standard, involving a temperature of 25 °C (298 K) and a pressure of 100 kPa

Stoichiometry the relationship between relative quantities of reactants and products in a chemical reaction

Mass to mass calculations involving combustion 3.1.9.1

As we have learned in lesson 1D, thermochemical equations tell us the molar ratio of reactants and products of combustion, as well as the amount of energy released from combustion reactions. **Stoichiometry** can be used to convert masses of fuels to masses of other reactants or products in combustion equations.

How do we convert between masses of species in combustion reactions?

There are often situations where it is more convenient to measure the quantities of reactants and products of a chemical reaction by their mass, rather than in molar amounts. Given the mass of a known species in a reaction, to calculate the unknown mass or number moles of another species in a reaction, we need to follow these steps.

- Using atomic mass values provided in the periodic table and molecular formulas, determine the molar mass of the known ('given') and unknown ('desired') species.
- Convert known substance mass to an amount (in mol) using the formula $n = \frac{m}{M}$ where n represents the amount in moles (mol), m represents the mass in grams (g), and M represents the molar mass of the species in grams per mol ($g\ mol^{-1}$).
- Multiply the number of moles of the known substance by the stoichiometric ratio from the balanced (thermo)chemical equation to determine the number of moles of the unknown substance.
- If a mass is required, convert the number of moles of the unknown substance to a mass using the formula $m = n \times M$.
- Ensure that your answer has the appropriate units and number of significant figures.

STRATEGY

When performing calculations in chemistry, always keep the maximal number of digits in your calculator: do not round or truncate on your calculator. When writing method steps, you do not need to write all digits from your calculator, but it is best practice to write at least one more significant figure than the number of significant figures your answer will be given to. Only round to the appropriate number of significant numbers (which is the lowest number of significant figures used in calculation) when giving your final answer. Otherwise, rounding error may be introduced.

USEFUL TIP

The formula $n = \frac{m}{M}$ is provided in the VCE Data Book.

STRATEGY

Recall from VCE chemistry Units 1 & 2 that the relationship between the known and unknown species in a chemical reaction is given by:

$$n(\text{unknown}) = \frac{\text{coefficient of the unknown species}}{\text{coefficient of the known species}} \times n(\text{known})$$

WORKED EXAMPLE 1

3.00 kg of ethane gas undergoes combustion in an excess of oxygen according to the following equation.

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(g)$$

Calculate the mass, in grams, of CO_2 produced if the reaction goes to completion.

What information is presented in the question?

The mass of C_2H_6 that reacts.

The balanced equation for the combustion of ethane.

What is the question asking us to do?

Calculate the mass, in grams, of CO_2 produced.

What strategies do we need in order to answer the question?

1. Convert $m(C_2H_6)$ to grams.
2. Determine $n(C_2H_6)$, our known amount.
3. Calculate $n(CO_2)$, our unknown amount.
4. Determine $m(CO_2)$ to answer the question.

Answer

$m(C_2H_6)$ (in grams) $= 3.00\ kg \times 1000$

$m(C_2H_6) = 3000\ g$

$M(C_2H_6) = (2 \times 12.0\ g\ mol^{-1}) + (6 \times 1.0\ g\ mol^{-1})$

$M(C_2H_6) = 30.0\ g\ mol^{-1}$

$n(C_2H_6) = \frac{m}{M}$

$n(C_2H_6) = \frac{3000\ g}{30.0\ g\ mol^{-1}}$

$n(C_2H_6) = 100\ mol$

$n(C_2H_6) : n(CO_2)$

$1 \quad : \quad 2$

$n(CO_2) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$

$n(CO_2) = \frac{2}{1} \times 100\ mol$

$n(CO_2) = 200\ mol$

$M(CO_2) = 12\ g\ mol^{-1} + (2 \times 16.0)\ g\ mol^{-1}$

$M(CO_2) = 44.0\ g\ mol^{-1}$

$m(CO_2) = 200\ mol \times 44.0\ g\ mol^{-1}$

$m(CO_2) = 8800\ g$

Therefore, 8.80×10^3 g of CO_2 is produced.

PROGRESS QUESTION

Question 1

Methane gas combusts in excess oxygen according to the equation

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

If 18 g of H_2O was produced from this reaction, what mass of methane was combusted?

A. 8.0 g

B. 9.0 g

C. 16 g

D. 18 g

Mass to volume calculations involving combustion 3.1.9.2

Given the mass of a reactant or product of a balanced chemical equation, we can also calculate the volume of any gaseous species in the reaction at **standard laboratory conditions (SLC)**. This includes calculation of the total mass or volume of greenhouse gases produced in a combustion reaction.

How do we convert between masses and volumes of species in combustion reactions?

USEFUL TIP

Any calculation questions involving volumes of gases in VCAA exams from 2024 onwards will be at SLC. The ideal gas equation is no longer required knowledge in Units 3 & 4.

In VCE chemistry Units 1 & 2, we were introduced to standard laboratory conditions (SLC): a temperature of 25 °C and a pressure of 100 kPa. We also learned that at SLC, the **molar volume of gases** (volume occupied by one mole of any gas) is 24.8 L mol^{-1}, a value provided in the VCE Data Book. For any reaction occurring at SLC, to convert between the volume of a gaseous species and the number of moles of this species, we use the formula:

$$n = \frac{V}{V_m}$$

where n represents the amount in moles (mol), V represents the volume in litres (L), and V_m represents the molar volume at SLC (24.8 L mol^{-1}).

MISCONCEPTION

'V_m is measured in mol L^{-1} (M).'

V_m is measured in L mol^{-1} (litres per mole), a different unit from mol L^{-1} (moles per litre, M), which is the unit of molar concentration.

WORKED EXAMPLE 2

At SLC, methane gas undergoes complete combustion according to the following reaction.

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

In a reaction vessel at SLC, 2.50 g of H_2O is produced.

Calculate the volume of methane that must have been present in the reaction vessel.

What information is presented in the question?

The balanced equation for the complete combustion of methane.

The reaction is occurring at SLC.

2.50 g of H_2O is produced.

Continues →

What is the question asking us to do?

Find the volume of methane that has been combusted.

What strategies do we need in order to answer the question?

1. Calculate $n(H_2O)$.
2. Use molar ratios to find $n(CH_4)$.
3. Use the molar volume of a gas to find $V(CH_4)$.

Answer

$$n(H_2O) = \frac{m}{M}$$

$$n(H_2O) = \frac{2.50\text{ g}}{18.0\text{ g mol}^{-1}}$$

$$n(H_2O) = 0.1388\text{ mol}$$

$$n(H_2O) : n(CH_4)$$

$$2 \quad : \quad 1$$

$$n(CH_4) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$$

$$n(CH_4) = \frac{1}{2} \times 0.1388\text{ mol}$$

$$n(CH_4) = 0.06944\text{ mol}$$

$$V(CH_4) = n \times V_m$$

$$V(CH_4) = 0.06944\text{ mol} \times 24.8\text{ L mol}^{-1}$$

$$V(CH_4) = 1.72\text{ L}$$

How do we calculate the quantity of greenhouse gases produced by combustion reactions?

All combustion reactions involve at least one of the greenhouse gases, which are of particular interest in green chemistry, as they may contribute to the enhanced greenhouse effect and hence global warming. The major greenhouse gases involved in combustion reactions are water vapour (H_2O), carbon dioxide (CO_2), and methane (CH_4). Using the stoichiometric techniques explored in this lesson, we can calculate the total mass or volume of greenhouse gases produced in the combustion of a given fuel.

MISCONCEPTION

'Water vapour is not a potent greenhouse gas.'

Of all the greenhouse gases, water vapour is the most potent contributor to the greenhouse effect. Conversely, carbon dioxide is the least potent, yet at high volumes it can have a massive effect.[1]

KEEN TO INVESTIGATE?

[1] **How does water vapour contribute to the greenhouse effect?**
Search: How atmospheric water vapour amplifies Earth's greenhouse effect

Particularly for the combustion of methane, we can also calculate the net mass or net volume of greenhouse gases produced by a given combustion reaction, using the formula:

Net amount = amount produced − amount consumed

Methane is ten times more potent (strong) as a greenhouse gas than carbon dioxide. As a result, the combustion of methane to produce carbon dioxide can be a 'net-green' process if the alternative is the release of methane into the atmosphere.

Additionally, since water is a liquid at 25 °C, for any combustion reaction occurring at SLC, water should be written in the liquid phase: $H_2O(l)$. This means that at SLC, H_2O does not contribute to the total amount of greenhouse gases produced. However, under non-standard conditions, H_2O may be a gas and hence contribute to the amount of greenhouse gases produced.

USEFUL TIP

At SLC (298 K or 25 °C), water is always a liquid.

WORKED EXAMPLE 3

Under non-standard conditions, methane gas undergoes complete combustion in an excess of oxygen according to the following reaction.

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

In a reaction vessel under these conditions, 10.0 g of CH_4 is combusted. Calculate the net change in mass of greenhouse gases as a result of this reaction.

What information is presented in the question?

The balanced equation for the complete combustion of methane.

The reaction is occurring under non-standard conditions.

10.0 g of CH_4 is combusted.

What is the question asking us to do?

Calculate the net change in mass of greenhouse gases as a result of this reaction.

What strategies do we need in order to answer the question?

1. Identify all greenhouse gases present in the products.
2. Calculate the total mass of greenhouse gas products.
3. Identify all greenhouse gases present in the reactants.
4. Calculate the total mass of greenhouse gas reactant.
5. Calculate the net change in mass of greenhouse gases during the reaction.

Answer

The products CO_2 and H_2O are greenhouse gases.

$n(CH_4) = \frac{m}{M}$

$n(CH_4) = \frac{10.0\text{ g}}{16.0\text{ g mol}^{-1}}$

$n(CH_4) = 0.625\text{ mol}$

$n(CO_2) : n(CH_4)$

$1 \quad : \quad 1$

$n(CO_2) = 0.625\text{ mol}$

$m(CO_2) = n \times M$

$m(CO_2) = 0.625\text{ mol} \times 44.0\text{ g mol}^{-1}$

$m(CO_2) = 27.5\text{ g}$

$n(H_2O) : n(CH_4)$

$2 \quad : \quad 1$

$n(H_2O) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$

$n(H_2O) = \frac{2}{1} \times 0.625\text{ mol}$

$n(H_2O) = 1.25\text{ mol}$

$m(H_2O) = n \times M$

$m(H_2O) = 1.25\text{ mol} \times 18.0\text{ g mol}^{-1}$

$m(H_2O) = 22.5\text{ g}$

Total mass of greenhouse gases produced = $m(CO_2) + m(H_2O)$

Total mass of greenhouse gases produced = 27.5 g + 22.5 g

Total volume of greenhouse gases produced = 50.0 g

The reactant CH_4 is a greenhouse gas.

$m(CH_4) = 10.0\text{ g}$

Net change in mass of greenhouse gases = mass produced − mass reacted

Net change in mass of greenhouse gases = 50.0 g − 10.0 g

Net change in mass of greenhouse gases = 40.0 g

Therefore, this reaction results in a net increase of 40.0 g of greenhouse gases.



Image: Douglas Cliff/Shutterstock.com

Figure 1 Prices of petrol are usually given in cost per litre (volume of liquid).

STRATEGY

Some past VCAA exam questions have involved density calculations, as we are often interested in the volume of liquid fuels (figure 1). We can use the equation density = $\frac{\text{mass}}{\text{volume}}$ to convert between density, mass, and volume. The units given in the VCE Data Book for the density of water (g mL^{-1} or kg L^{-1}) can help you determine this formula if you forget.

PROGRESS QUESTIONS

Question 2

Which of the following is not a greenhouse gas?

A. CO **B.** CO_2 **C.** CH_4 **D.** H_2O

Question 3

If a reaction produces 10 L of $CO_2(g)$ at SLC, what mass of $CO_2(g)$ is produced?

A. 0.40 g **B.** 10 g **C.** 18 g **D.** 440 g

Volume to volume calculations involving combustion 3.1.9.3

Combustion reactions involve gaseous reactants and products, and so it is often desirable to calculate the volume of these gases involved in a reaction.

How do we convert between volumes of gases in combustion reactions?

In worked example 3, we found that the volumes of CH_4, CO_2, and H_2O in the equation were in a 1 : 1 : 2 ratio, equivalent to the 1 : 1 : 2 molar ratio of the corresponding equation. This tells us that to convert between volumes of gaseous species in combustion reactions at SLC, we do not need to first convert these volumes to moles (unlike when converting between masses, since not all species have the same mass per mole).

STRATEGY

We can convert between volumes of gaseous species directly using molar ratios, without needing to convert to and from a number of moles.

Recall from Units 1 & 2 that all gases are assumed to occupy the same volume per mole at a given temperature and pressure. At SLC, 1 mol of any gas occupies 24.8 L mol^{-1}, and so when given a balanced combustion equation, we can convert the volume of one gaseous species to the volume of another simply by using the formula

$$V(\text{unknown}) = \frac{\text{coefficient of the unknown volume}}{\text{coefficient of the known volume}} \times V(\text{known})$$

which is analogous to the formula for converting between molar amounts of different species. VCE chemistry only covers such calculations for reactions occurring at SLC, but this formula holds for any constant temperature or pressure.

WORKED EXAMPLE 4

Gaseous pentan-1-ol undergoes complete combustion in the presence of excess oxygen according to the following reaction.

$2C_5H_{11}OH(g) + 15O_2(g) \rightarrow 10CO_2(g) + 12H_2O(g)$

If 5.30 L of pentan-1-ol is burnt in the presence of excess oxygen at SLC, calculate the volume of carbon dioxide produced.

What information is presented in the question?

The balanced equation for the complete combustion of pentan-1-ol.

The initial volume of pentan-1-ol.

The reaction is occurring at SLC.

What is the question asking us to do?

Find the volume of CO_2 that is produced.

What strategy do we need in order to answer the question?

Use the molar ratios of the reaction to determine the unknown volume.

Answer

$$V(\text{unknown}) = \frac{\text{coefficient of the unknown species}}{\text{coefficient of the known species}} \times V(\text{known})$$

$$V(CO_2) = \frac{\text{coefficient of unknown volume}}{\text{coefficient of known volume}} \times V(C_5H_{11}OH)$$

$$V(CO_2) = \frac{10}{2} \times V(C_5H_{11}OH)$$

$$V(CO_2) = \frac{10}{2} \times 5.30 \text{ L}$$

$$V(CO_2) = 26.5 \text{ L}$$

This assumes that temperature and pressure remain constant over the course of the reaction, which (although not always realistic) is an assumption that can be made in VCE chemistry.

PROGRESS QUESTION

Question 4

Butane combusts in excess oxygen according to the equation

$$C_4H_{10}(g) + \frac{13}{2}O_2(g) \rightarrow 4CO_2(g) + 5H_2O(g)$$

If 13 L of butane gas is combusted at SLC in excess oxygen, what volume of CO_2 is produced?

A. 13 L

B. 26 L

C. 39 L

D. 52 L

Enthalpy changes 3.1.9.4

Given a balanced thermochemical equation and a given quantity of a reactant or product, we can also calculate the total amount of energy released in a combustion reaction.

How do we calculate the amount of heat produced in combustion reactions?

Recall from lesson 1D that combustion reactions are exothermic: they result in a net release of heat energy. We were also introduced to thermochemical equations, which tell us the exact quantity of heat energy (usually in kJ or kJ mol^{-1}) released in the combustion of a set number of moles of a fuel. Yet, often, we are interested in calculating the amount of energy released from a different quantity of a fuel: for instance, 100 grams of octane, or 50 litres of ethanol. When working with pure fuels, we must first convert the quantity of fuel to an amount in mol, using the equations:

$$n = \frac{m}{M} \text{ and } n = \frac{V}{V_m}$$

Then, we use the **molar heat of combustion** (in kJ mol^{-1}, which we may need to calculate first) to determine the total energy released in combustion, according to the formula:

energy released = molar heat of combustion × n(fuel)

For common fuels, the VCE Data Book provides:

- heat of combustion per mole of fuel (for pure fuels only), measured in kJ mol^{-1}
- heat of combustion per gram of fuel (for pure fuels and blended fuels), measured in kJ g^{-1}.

The latter allows us to calculate the energy released from the combustion of a given mass of a mixture, like diesel or natural gas, or a given mass of a pure fuel (without us having to convert to a number of moles first). These heat of combustion values are provided in table 1 for pure fuels, and table 2 for blended fuels.

MISCONCEPTION

'Energy change values for a given fuel are fixed.'

The amount of energy released (kJ) from combustion of a given quantity of fuel depends on the pressure and temperature of the system. The fixed values in the VCE Data Book are the molar heat of combustion values (kJ mol^{-1}), which are accurate only under Standard Laboratory Conditions (SLC).

Table 1 Heats of combustion of common pure fuels

Fuel	Formula	State	Heat of combustion (kJ g^{-1})	Molar heat of combustion (kJ mol^{-1})
Hydrogen	H_2	Gas	141	282
Methane	CH_4	Gas	55.6	890
Propane	C_3H_8	Gas	50.5	2220
Octane	C_8H_{18}	Liquid	47.9	5460
Ethanol	C_2H_5OH	Liquid	29.6	1360

STRATEGY

When given a mass of a common fuel and asked for the amount of energy produced from its combustion, simply multiply the mass of the fuel by its heat of combustion in kJ g^{-1} (in the VCE Data Book).

Table 2 Heats of combustion of common blended fuels

Fuel	State	Heat of combustion (kJ g^{-1})
Kerosene	Liquid	46.2
Diesel	Liquid	45.0
Natural gas	Gas	54.0

USEFUL TIP

Blended fuels (e.g. kerosene) are mixtures, and so their amount cannot sensibly be expressed in mol. As a result, the VCE Data Book gives their heat of combustion only in kJ g^{-1}, not in kJ mol^{-1}.

Figure 2 summarises the various formulas used to convert between quantities in this lesson.

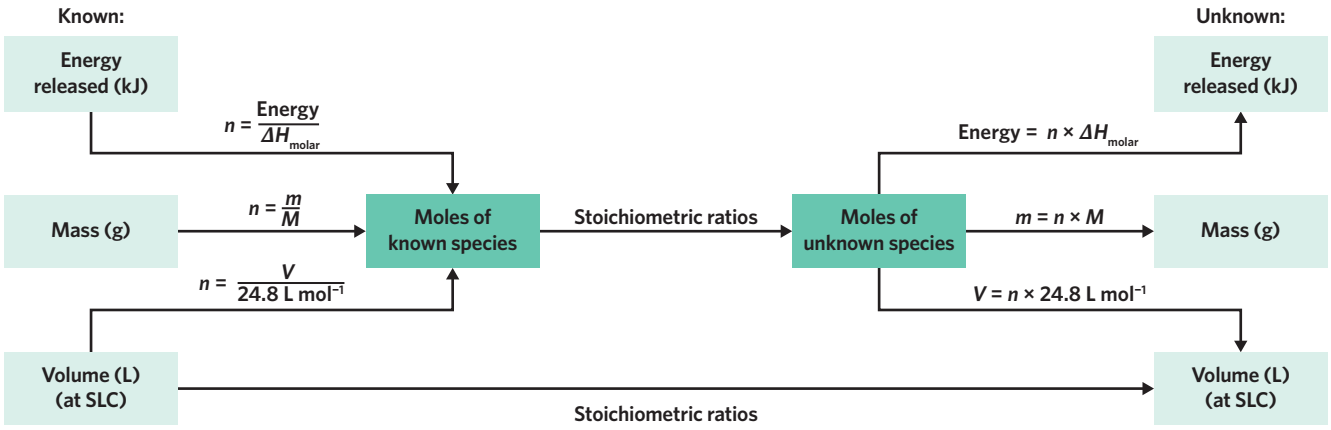


Figure 2 Summary of methods to convert between energy released by a fuel, volume, and mass

WORKED EXAMPLE 5

Ethanol is a fuel that combusts in excess oxygen according to the following thermochemical equation.

$C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \quad \Delta H = -1360\ \text{kJ mol}^{-1}$

Determine the amount of energy released (in kJ) if ethanol is combusted in excess oxygen to produce 100 g of CO_2.

What information is presented in the question?

Ethanol is combusted in excess oxygen.

The molar heat of combustion of ethanol.

The volume of carbon dioxide produced.

What is the question asking us to do?

Calculate the amount of energy released during this reaction.

What strategies do we need in order to answer the question?

1. Calculate the number of moles of CO_2 produced.
2. Use molar ratios to determine the number of moles of ethanol combusted.
3. Use the ΔH to determine the total energy released.

Continues →

Answer

$M(CO_2) = 12.0\ g\ mol^{-1} + (2 \times 16.0\ g\ mol^{-1})$

$M(CO_2) = 44.0\ g\ mol^{-1}$

$n(CO_2) = \frac{m}{M}$

$n(CO_2) = \frac{100\ g}{44.0\ g\ mol^{-1}}$

$n(CO_2) = 2.2727\ mol$

$n(C_2H_5OH) : n(CO_2)$

1 : 2

$n(C_2H_5OH) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$

$n(C_2H_5OH) = \frac{1}{2} \times 2.2727\ mol$

$n(C_2H_5OH) = 1.136\ mol$

Energy released $= -\Delta H_{molar} \times n(C_2H_5OH)$

Energy released $= 1360\ kJ\ mol^{-1} \times 1.136\ mol$

Energy released $= 1545\ kJ$

Energy released $= 1.55 \times 10^3\ kJ$ (3 sig. figs)

PROGRESS QUESTIONS

Question 5

How much energy is released when 43.0 g of ethanol is combusted in excess oxygen?

A. 1.27×10^3 kJ **B.** 5.85×10^4 kJ **C.** 6.36×10^2 kJ **D.** 1.36×10^3 kJ

Question 6

How much energy is produced when 50.0 L of hydrogen gas is combusted at SLC?

A. 7.05×10^3 kJ **B.** 5.69×10^2 kJ **C.** 3.50×10^5 kJ **D.** 14.1×10^4 kJ

Theory summary

- By using balanced chemical equations and the formula $n = \frac{m}{M}$, the unknown mass of a reactant or product in a combustion reaction can be determined.
- The unknown volume of a gaseous reactant or product can be calculated at SLC (25 °C and 100 kPa) using balanced equations and the standard molar volume of gases (24.8 L mol^{-1}).
- For any reaction occuring at SLC, to convert between the volume of a gaseous species and the number of moles of this species, we use the formula: $n = \frac{V}{V_m}$
- When converting between masses and volumes in a combustion reaction, use the amount in mol (n) of all quantities as the 'unit of exchange'.
- These methods can also be used to determine the net volume or mass of greenhouse gases produced in combustion reactions, including CH_4, CO_2, and H_2O.
- Based on molar enthalpy of combustion values (measured in kJ mol^{-1} and kJ g^{-1}) given in thermochemical equations or the VCE Data Book, the enthalpy change of combustion reactions can also be calculated.

2A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

Over 40 countries around the world use E10 unleaded fuel, which consists of a blend of 90% octane and 10% ethanol (by mass). A full tank of E10 unleaded fuel produces 2.396×10^6 kJ of energy when it undergoes complete combustion at SLC. A car manufacturer wishes to calculate the mass of E10 fuel that produces this amount of energy.

Question 7 (1 MARK)

1.00 g of E10 unleaded fuel contains

A. 0.10 g of octane and 0.90 g of ethanol.
B. 0.29 g of octane and 0.71 g of ethanol.
C. 0.71 g of octane and 0.29 g of ethanol.
D. 0.9 g of octane and 0.1 g of ethanol.

Question 8 (1 MARK)

The heats of combustion (in kJ g^{-1}) of octane and ethanol are

A. 0.0479 kJ g^{-1} for octane, 0.0296 kJ g^{-1} for ethanol.
B. 5.46 kJ g^{-1} for octane, 1.36 kJ g^{-1} for ethanol.
C. 47.9 kJ g^{-1} for octane, 29.6 kJ g^{-1} for ethanol.
D. 5460 kJ g^{-1} for octane, 1360 kJ g^{-1} for ethanol.

Question 9 (2 MARKS)

Calculate the mass of E10 fuel (in g) in a full tank.

Adapted from VCAA (NHT) 2021 exam Multiple choice Q13

Exam-style

Question 10 (1 MARK)

One possible reaction that can occur when trinitrotoluene (TNT), $C_7H_5N_3O_6$, explodes is

$2C_7H_5N_3O_6(s) \rightarrow 2C(s) + 12CO(g) + 5H_2(g) + 3N_2(g)$

When one mole of TNT explodes at SLC, the total volume of the gases produced from this reaction is closest to

A. 248 L **B.** 273 L **C.** 496 L **D.** 546 L

Adapted from 2010 Exam 1 Multiple choice Q5

Question 11 (1 MARK)

What is the total energy released, in kilojoules, when 100 g of butane and 200 g of octane undergo combustion in the presence of excess oxygen?

A. 9760 **B.** 14 600 **C.** 17 300 **D.** 19 500

VCAA 2017 exam Multiple choice Q7

Question 12 (7 MARKS)

A chemist tasked with investigating the relative environmental impact of different fuels decided to compare octane and ethanol. Since these fuels are used on such a large scale, they reasoned that a relevant way of comparing them would be to calculate the volume of greenhouse gases each fuel produced for each MJ of energy they provided.

The thermochemical equations for the combustion of octane and ethanol are shown. Assume each reaction goes to completion with an excess of oxygen supplied.

$C_8H_{18}(g) + \frac{25}{2}O_2(g) \rightarrow 8CO_2(g) + 9H_2O(l) \quad \Delta H = -5460 \text{ kJ mol}^{-1}$

$C_2H_5OH(g) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \quad \Delta H = -1360 \text{ kJ mol}^{-1}$

a. To produce 1.000 MJ (1.000 MJ = 1.000×10^6 J) of energy, calculate the required amount (in mol) of:

i. Octane 1 MARK

ii. Ethanol 1 MARK

b. If the experiment is performed under SLC, for every 1.000 MJ of energy obtained, calculate the total **amount** (in mol) of CO_2 produced by the combustion of:

i. Octane 1 MARK

ii. Ethanol 1 MARK

c. If the experiment is performed under SLC, for every 1.000 MJ of energy obtained, calculate the total **volume** (in L) of CO_2 produced by the combustion of:

i. Octane 1 MARK

ii. Ethanol 1 MARK

d. Based on your answer to part **c**, explain which of the two fuels contributes least to the enhanced greenhouse effect when combusted at SLC. 1 MARK

Question 13 (5 MARKS)

Propane undergoes combustion at SLC according to the following thermochemical equation.

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l) \quad \Delta H = -2220 \text{ kJ mol}^{-1}$

a. If 2.3 g of propane undergoes complete combustion, calculate the volume of CO_2 produced at SLC. 3 MARKS

b. If the 2.3 g of propane were instead burnt in its liquid form, would this reaction produce more or less energy per mole of fuel than if it were burnt in its gaseous form? Justify your answer. 2 MARKS

Question 14 (10 MARKS)

After retiring, Mel is planning to take a caravan around Australia, towed along by her ute. She tests three different fuels – diesel, petrol, and LPG – and determines their fuel economy (in L per 100 km) when used in her ute. From this data, as well as some other information she finds from research, she aims to determine which fuel will produce the least mass of CO_2 per 100 km driven, and to use this fuel in her ute.

Assume that petrol is entirely octane and combusts according to the equation:

$C_8H_{18}(g) + \frac{25}{2}O_2(g) \rightarrow 8CO_2(g) + 9H_2O(l)$

And assume that LPG is entirely propane and combusts according to the equation:

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$

		a)	**b)**	**c)**
Fuel	**Fuel economy (L per 100 km)**	**Density (kg L^{-1})**	**Mass of fuel used per 100 km (kg per 100 km)**	**Mass of CO_2 produced per 100 km (kg per 100 km)**
Diesel	12.0	0.838		31.6
LPG (propane)	19.7	0.493		
Petrol (octane)	18.9		14.0	

For Mel's incomplete table,

a. Complete column **a)** for petrol. 1 MARK

b. Complete column **b)** for:

i. Diesel 1 MARK

ii. LPG 1 MARK

c. Complete column **c)** for:

i. LPG 3 MARKS

ii. Petrol 3 MARKS

d. According to her aim, which fuel should Katrina use? 1 MARK

Key science skills

Question 15 🌶🌶 (6 MARKS)

Having heard about the success of E10 fuel, Louis, a researcher for a petrol company, develops a fuel containing a mixture of approximately 80% octane, and 20% ethanol (by mass), with some variation across batches. They design an experiment to estimate this fuel's average heat of combustion in kJ g^{-1}.
Their results are as follows.

	Trial #1	Trial #2	Trial #3	Average
Mass of fuel combusted (g)	10.0	10.0	10.0	10.0
Energy produced (kJ)	446	436	433	438
Calculated heat of combustion (kJ g^{-1})				43.8

a. On their second attempt, Louis accidentally uses methanol instead of ethanol in the fuel mixture. Explain why this trial would not be considered valid. 1 MARK

b. Did this error cause an increase or decrease in the final calculated value for the fuel mixture's heat of combustion (in kJ g^{-1})? Justify your answer. 3 MARKS

c. The company's marketing manager Gustavo wants to calculate this fuel mixture's molar heat of combustion, to better compare it with other fuels. Explain why this is not suitable, with reference to repeatability. 2 MARKS

FROM LESSON 12D

Questions from multiple lessons

Question 16 🌶🌶 (5 MARKS)

Internal combustion engines are used in large numbers of motor vehicles. Traditionally, petrol (predominantly octane) has been used as fuel, but in recent years, alternatives have been explored.

a. A common method is to blend petrol with ethanol in varying ratios. A fuel can be obtained by blending 1.00 mol of octane, C_8H_{18}, and 1.00 mol of ethanol, C_2H_5OH. The chemical equation for the complete combustion of this fuel mixture is

$$C_8H_{18}(l) + C_2H_5OH(l) + \frac{31}{2}O_2(g) \rightarrow 10CO_2(g) + 12H_2O(g)$$

Calculate the energy released, in kilojoules, when 80 g of this fuel mixture undergoes complete combustion. Show your working. 3 MARKS

Adapted from VCAA 2019 exam Short answer Q4a

b. Explain one advantage of using ethanol, rather than purely petrol, in motor vehicles. 2 MARKS

FROM LESSON 1B

Question 17 🌶🌶🌶 (12 MARKS)

Both hydrogen and methane can be burned to produce energy.

a. Write balanced thermochemical equations for the complete combustion, at SLC, of:

i. Hydrogen 2 MARKS

ii. Methane 2 MARKS

b. Calculate the volume of hydrogen gas (in L) that produces the same amount of energy as 2.0 L of methane gas at SLC. 4 MARKS

VCAA 2010 Exam 2 Short answer Q1biii

c. Another important consideration for fuels is the volume of greenhouse gases produced. For the combustion reactions of 1 mole of hydrogen and 1 mole of methane at SLC:

i. Which combustion reaction (if any) produces a greater **total** (gross) volume of greenhouse gases? Use numerical evidence to support your answer. 2 MARKS

ii. Which combustion reaction (if any) results in a greater **net** increase in volume of greenhouse gases? Use numerical evidence to support your answer. 2 MARKS

FROM LESSON 1D

Back to contents

2B Calculating energy changes using water

STUDY DESIGN DOT POINTS

- the use of specific heat capacity of water to approximate the quantity of heat energy released during the combustion of a known mass of fuel and food
- the principles of solution calorimetry, including determination of calibration factor and consideration of the effects of heat loss; analysis of temperature-time graphs obtained from solution calorimetry

2A 2B 2C

- 3.1.10.1 Specific heat capacity
- 3.1.11.1 Principles of calorimetry
- 3.1.11.2 Solution calorimetry

ESSENTIAL PRIOR KNOWLEDGE

2A Energy from combustion

See question 13.



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How many cups of tea does it take to cause an energy crisis?

At certain times of the day in Great Britain, millions of people simultaneously turn on their kettles to make tea. This has been the cause of a momentary shortage of energy, known as the 'Great British Kettle Surge'. Heating water is not only useful for making tea: it is also an effective method of determining the energy content of a fuel or food. In this lesson we will explore this method, as well as the concept of **solution calorimetry**.

KEY TERMS AND DEFINITIONS

Calibrate adjust an instrument to ensure it produces accurate results

Calibration factor amount of energy (in J or kJ) required to be released/absorbed in a given calorimeter to increase/decrease water temperature by 1 °C

Calorimeter insulated vessel designed to minimise and account for heat loss

Extrapolate extend a graph to infer new values outside the range of data

Solution calorimetry use of a calorimeter to estimate the enthalpy change of a reaction that occurs in solution

Specific heat capacity energy (J) required to raise the temperature of 1 gram of a given substance by 1 °C

Temperature-time graph graph that plots change in temperature over time (particularly for a calorimetry experiment)

Specific heat capacity 3.1.10.1

In the VCE Data Book, values for the amount of energy in fuels and food are given, and nutritional information panels on packaging often tell us the energy content of foods. These values are determined by experimentation, and one method for indirectly determining them involves measuring the temperature change of water when these fuels and foods are combusted.

How can we use water to estimate the amount of energy in a fuel or food?

Recall from Unit 1 that it takes a set amount of energy to raise the temperature of 1 gram of a substance by 1 °C; this amount of energy is called the substance's **specific heat capacity** value, and is measured in units J g^{-1} $°C^{-1}$.

Liquid water has a relatively high specific heat capacity value of 4.18 J g^{-1} $°C^{-1}$. In an experiment, we can determine the quantity of heat energy absorbed by a given mass of water using the equation

$q = mc\Delta T$

where:

- q is the quantity of energy absorbed by the water (J)
- m is the mass of water (g)
- c is the specific heat capacity of water (4.18 J g^{-1} $°C^{-1}$)
- ΔT is the change in temperature of the water (°C)

This equation can be used to estimate the energy released by combustion of a fuel or food. To do this:

1. Set up apparatus as shown in figure 1.
2. Fill the vessel (ideally well-insulated) with water and record the water's mass, m (in grams), and initial temperature, $T_{initial}$ (in °C).
3. Combust the fuel for a period of time, then record the total mass of fuel or food combusted, m(fuel combusted) (in grams), and the final temperature of the water, T_{final} (in °C) (which usually continues to rise after the flame is extinguished).
4. Calculate q (the energy absorbed by the water, in J) using the equation $q = mc\Delta T$, where m is the mass of water (in grams), $c = 4.18$ J g^{-1} $°C^{-1}$, and $\Delta T = T_{final} - T_{initial}$.
5. Estimate the amount of heat energy released per gram of the fuel or food combusted (in J g^{-1}) using the formula energy per gram $= \frac{q}{m(\text{fuel combusted})}$, or the molar heat of combustion (in J mol^{-1}) using the formula molar heat of combustion $= \frac{q}{n(\text{fuel combusted})}$.

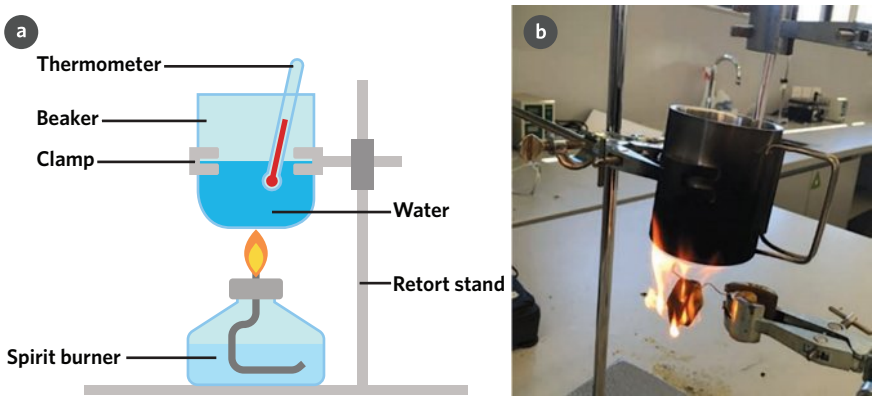


Figure 1 Apparatus for using water to estimate heat released by **(a)** a liquid fuel, and **(b)** a food sample

USEFUL TIP

Liquid fuels are usually combusted by first placing them in spirit burners (to minimise safety hazards), whereas foodstuffs can sometimes be ignited directly. Gaseous fuels usually require specific apparatus.

For pure fuels, the molar heat of combustion (in kJ mol^{-1}) can also be estimated by converting the mass of fuel combusted to a molar amount, using the formula $n = \frac{m}{M}$.

STRATEGY

ΔT can be calculated using the equation $\Delta T = T_{final} - T_{initial}$

USEFUL TIP

At SLC, the density of water is 0.997 g mL^{-1}. However, in VCAA exams, it is acceptable to use either 0.997 g mL^{-1} or 1.00 g mL^{-1}.

WORKED EXAMPLE 1

Khalid performs an experiment to estimate the molar heat of combustion of ethanol. His results were as follows:

	Mass of ethanol + spirit burner (g)	Mass of water (g)	Temperature of water (°C)
Initial	251.3	200.0	22.4
Final	249.1	200.0	30.2

Based on Khalid's data, calculate ethanol's heat of combustion (in kJ mol^{-1}).

What information is presented in the question?

The initial and final masses of the spirit burner containing ethanol.

The initial and final masses of the water.

The initial and final temperatures of the water.

What is the question asking us to do?

Calculate the amount of energy absorbed by the water per mole of ethanol combusted (in kJ mol^{-1}) in this experiment.

What strategies do we need in order to answer the question?

1. Calculate ΔT using $\Delta T = T_{final} - T_{initial}$.
2. Calculate the energy absorbed by the water using $q = mc\Delta T$.
3. Calculate the mass of fuel combusted using $m(\text{fuel combusted}) = m_{intial}(\text{fuel}) - m_{final}(\text{fuel})$.
4. Convert mass to number of moles using $n = \frac{m}{M}$.
5. Convert energy values in J to kJ by dividing by 10^3.
6. Calculate molar heat of combustion using the formula molar heat of combustion $= \frac{q}{n(\text{fuel})}$.

Answer

$\Delta T = T_{final} - T_{initial}$

$\Delta T = 30.2\ °C - 22.4\ °C$

$\Delta T = 7.8\ °C$

$m(\text{water}) = 200.0\ g$

$c(\text{water}) = 4.18\ J\ g^{-1}\ °C^{-1}$

$q = m \times c \times \Delta T$

$q = 200.0\ g \times 4.18\ J\ g^{-1}\ °C^{-1} \times 7.8\ °C$

$q = 6.5208 \times 10^3\ J$

$q = 6.5208 \times 10^3 \div 10^3\ kJ$

$q = 6.5208\ kJ$

$m(\text{ethanol combusted}) = m(\text{ethanol and burner, initial}) - m(\text{ethanol and burner, final})$

$m(\text{ethanol combusted}) = 251.3\ g - 249.1\ g$

$m(\text{ethanol combusted}) = 2.2\ g$

$n(\text{ethanol combusted}) = \frac{m}{M}$

$n(\text{ethanol combusted}) = \frac{2.2\ g}{46.0\ g\ mol^{-1}}$

$n(\text{ethanol combusted}) = 0.047826\ mol$

$\text{molar heat of combustion} = \frac{q}{n(\text{fuel})}$

$\text{molar heat of combustion} = \frac{6.5208\ kJ}{0.047826\ mol}$

$\text{molar heat of combustion} = 136\ kJ\ mol^{-1}$

$\text{molar heat of combustion} = 1.4 \times 10^2\ kJ\ mol^{-1}$ (2 sig. figs)

Therefore, the experimental value for ethanol's molar heat of combustion is $1.4 \times 10^2\ kJ\ mol^{-1}$.

MISCONCEPTION

'Heat is lost.'

Energy, including heat energy, cannot be created or lost; it is only transferred to other objects or transformed to other forms of energy. After water in a vessel is heated, heat from the water is transferred to the surrounding air and to the vessel itself, which is commonly referred to as 'heat loss'.

While this method can be useful as a relative measure (i.e. for comparing different fuels or foods), it has a number of limitations:

- A large quantity of heat energy released from the combustion of the fuel or food (often ~90%) is lost to the surroundings, producing inaccurate results.
- The temperature of the laboratory affects the amount by which the water temperature increases, limiting reproducibility of results.
- Not all fuels or foods are available in a form that can be safely and feasibly combusted.
- The mass of water being heated will actually decrease due to evaporation.

A method that addresses the inaccuracy caused by heat loss is explored in the remainder of this lesson.

PROGRESS QUESTIONS

Question 1

A fuel or food's heat of combustion can be estimated by

A. determining the change in mass of water when the fuel or food is mixed with the water.

B. determining the change in mass of water when the fuel or food is combusted below it.

C. determining the change in temperature of water when the fuel or food is mixed with the water.

D. determining the change in temperature of water when the fuel or food is combusted below it.

Question 2

A spirit burner containing methanol initially weighs 237.6 g. After this fuel is used to heat 250.0 g of water, the spirit burner and remaining methanol now weigh 232.2 g. The mass of fuel combusted is

A. 5.4 g **B.** 12.4 g **C.** 237.6 g **D.** 250.0 g

Question 3

In an experiment to determine a fuel's heat of combustion, 200.0 g of water increases in temperature from 22.3 °C, to 49.8 °C. What is the amount of energy absorbed by the water?

A. 18.6 kJ

B. 23.0 kJ

C. 41.6 kJ

D. 18 600 kJ

Principles of calorimetry 3.1.11.1

By comparing the result calculated in worked example 1 and ethanol's theoretical heat of combustion, we can see that the previous method can be significantly inaccurate. In lesson 2C, we will explore how this inaccuracy can be quantified and adjusted for. To more accurately estimate the amount of heat released from combustion of a substance, we can also use calorimetry, a method which minimises and accounts for heat loss, often producing more useful results.

What is calorimetry?

A **calorimeter** (figure 2) is an insulated reaction vessel, usually made of metal, designed to minimise the amount of heat lost by water to the surroundings and decrease the amount of variation in this heat loss (making it more consistent and hence measurable).

How is a calibration factor calculated and applied?

Even a well-insulated calorimeter still loses some heat. To account for this heat loss (which is assumed to be consistent), we determine how much energy input is required to raise the temperature of water in a given calorimeter by 1 °C: the **calibration factor**. This is called **calibrating** the calorimeter, for which there are two major methods.



Image: Victor Moussa/Shutterstock.com

Figure 2 Calorimeter used to measure enthalpy of a combustion reaction

Chemical calibration method

1. In the calorimeter, conduct an exothermic reaction with a known enthalpy change and a known quantity of fuel, then measure the temperature change of the water, ΔT.
2. Use stoichiometry (as explored in lesson 2A) to calculate the theoretical amount of energy released by the reaction, q.
3. Calculate the calibration factor (usually in J °C^{-1}) using the formula $\text{CF} = \frac{q}{\Delta T}$

Electrical calibration method

1. Connect the calorimeter to an electrical heating element, as shown in figure 3.
2. Switch on the heating element, and record the voltage (V, in volts) and current (I, in amperes) passed through the heating element.
3. After t seconds, switch off the heating element and record the water's temperature change, ΔT, during this period of time.
4. Calculate the quantity of energy, q, in joules (J), passed through the heating element using the formula $q = VIt$, where V is the applied voltage in volts (V), I is the current in amperes (A), and t, in seconds (s), is the length of time for which the current flows.
5. Calculate the calibration factor (in J °C^{-1}) using the formula $\text{CF} = \frac{q}{\Delta T}$

MISCONCEPTION

'$q = It$'

$Q = It$, where upper-case Q is electric charge (as will be further explored in lesson 3E).
$q = VIt$, where lower-case q is energy released. Case is important!

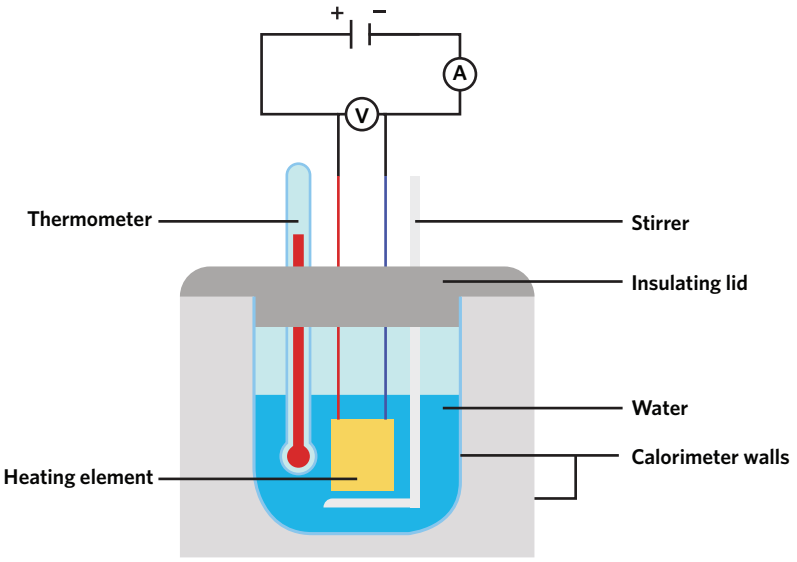


Figure 3 Heating element circuit diagram

KEEN TO INVESTIGATE?

[1] **How are the energy content values on food packaging determined?** Search YouTube: The science of a calorimeter

After completing either one of these methods to determine CF, to estimate the enthalpy change of a given 'unknown' reaction (such as the combustion of a fuel or food[1]):

1. Conduct this 'unknown' reaction in the same calorimeter.
2. Measure the temperature change of the water, ΔT.
3. Calculate the energy released (in J) using the formula $q = \text{CF} \times \Delta T$, where CF (in J °C^{-1}) is the value determined in the calibration stage.
4. As previously, q can be used to calculate the enthalpy change of the reaction per mole or per gram.

USEFUL TIP

For a given calorimeter in an experiment, we only need to calculate its calibration factor **once**. After that, we can use this calibration factor to estimate the enthalpy change of any number of unknown reactions, so long as they are conducted in the same calorimeter.

MISCONCEPTION

'Power must be turned on while calibrating the calorimeter, and while conducting the unknown reaction.'

Power must be turned on for the electrical calibration stage, but must **not** be turned on when the unknown reaction (for which we are seeking to determine the enthalpy change) is being conducted in the calorimeter. These two stages are separate.

Generally, the electrical method is considered more accurate, since for the chemical method, it is not always possible to determine exactly how much of a reactant was consumed or whether any incomplete combustion occurred, and it relies on a theoretical value which was likely determined under different conditions. Although a calibration factor can theoretically be calculated using any vessel (even an uninsulated glass beaker), a well-insulated vessel ensures that the amount of heat lost by the water is somewhat consistent, hence producing more precise and generally much more accurate results.

STRATEGY

When electrically calibrating using the formula $q = VIt$, q is in joules (J), but many questions require answers in kJ. To convert q in J to q in kJ, divide by 10^3, or multiply by 10^{-3}. These unit conversions are available in the VCE Data Book.

How do we interpret temperature-time graphs in calorimetry?

To visualise the results of a calorimetry experiment, we can construct a **temperature-time graph**, which plots the change in temperature of water over time in an experiment. To construct a temperature-time graph, the water temperature must be recorded at regular intervals prior to, during, and after the heating of the water. Figure 4 shows the temperature-time graph for a theoretically 'perfect' calorimeter with no heat loss.

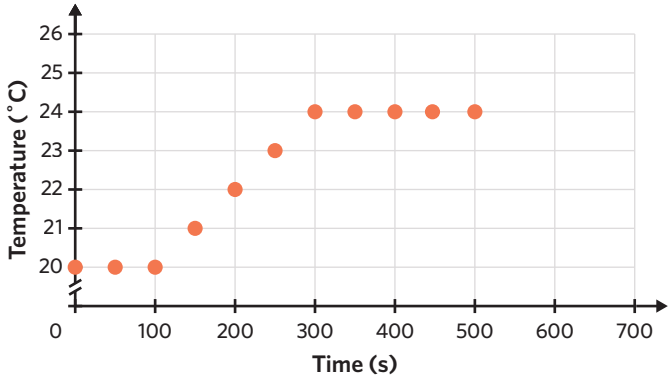


Figure 4 Temperature-time graph for a hypothetical, 'perfect' calorimetry experiment

In reality, even the best calorimeters have some heat loss, yet calculating a calibration factor using the water's overall temperature change during the experiment does not take into account the effect of ambient (room) temperature on the water temperature while the water is being heated. This may hence lead to variation in results when the experiment is performed at different temperatures (decreasing its validity and reproducibility). Figure 5 shows the temperature-time graph for a more realistic calorimetry experiment with some heat loss.

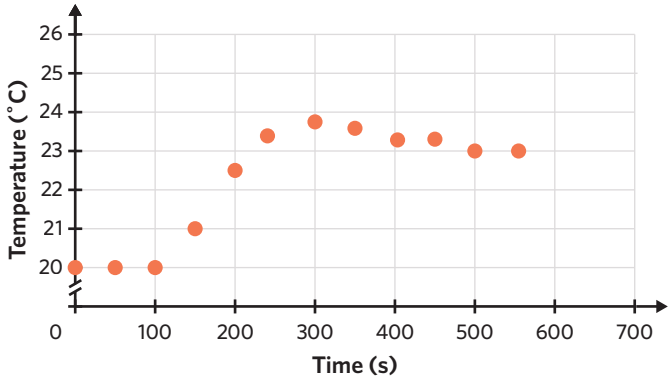


Figure 5 Temperature-time graph for a calorimetry experiment with some heat loss

When performing electrical calibration of a calorimeter, we can account and adjust for this inevitable heat loss by **extrapolating** a temperature-time graph. After the power is switched off, the water temperature gradually decreases. On the graph, we draw a line to fit this decrease, then extrapolate this line back to the point at which the power is switched on. We then take the difference between these two points as the 'adjusted' value of ΔT, as demonstrated in figure 6. Using this value of ΔT for calibration factor calculations leads to more accurate and reproducible results.

More frequent temperature measurements (smaller time intervals) generally produce more precise results, and the use of an electronic thermometer (attached to a datalogger) can increase resolution.

MISCONCEPTION

'Extrapolation always leads to inaccuracy.'

Although extrapolation is generally discouraged in chemistry, temperature-time graphs for calorimetry are one area in which extrapolation can in fact increase accuracy. VCAA will accept answers within a range to allow for slight variation.

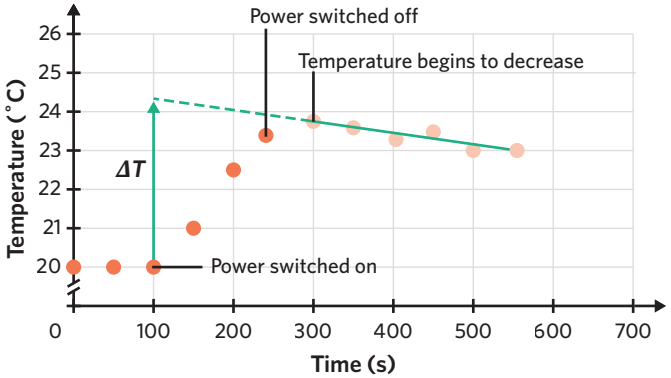
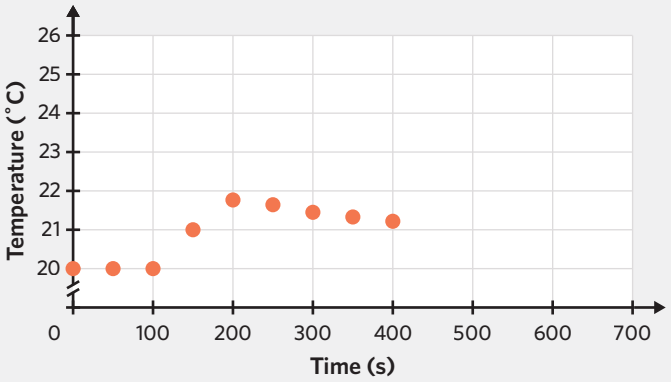


Figure 6 Use of extrapolation to determine ΔT for electrical calibration

Based on the extrapolation method, in figure 6, $\Delta T \approx 4.2$ °C. Alternatively, some past VCAA exam questions have taken ΔT to be the difference between the initial temperature and the maximum temperature (the point at which temperature begins to decrease). Using this alternative method in figure 6, $\Delta T = 3.7$ °C. This approach is simpler, but less accurate than the extrapolation method.

WORKED EXAMPLE 2

After learning about calorimetry, Khalid uses electrical calibration and a metal calorimeter to obtain a more accurate value for the heat of combustion of ethanol. He heats water in a calorimeter with a current of 1.2 A and a voltage of 5.0 V for 100 seconds, and constructs a temperature-time graph for this electrical calibration.



Khalid then fills the same calorimeter with the same volume of water, and combusts 0.010 mol of ethanol to heat this water. He measures the temperature rise to be 36.4 °C. Based on this calorimetry data, estimate the heat of combustion of ethanol in kJ mol^{-1}.

What information is presented in the question?

A voltage of 5.0 V was used to heat the water.

A current of 1.2 A was used to heat the water.

The heating element was switched on for 100 seconds.

A temperature-time graph for electrical calibration.

The amount of ethanol combusted was 0.010 mol.

The combustion of ethanol caused a temperature rise of 36.4 °C.

What is the question asking us to do?

Estimate the heat of combustion of ethanol in kJ mol^{-1}.

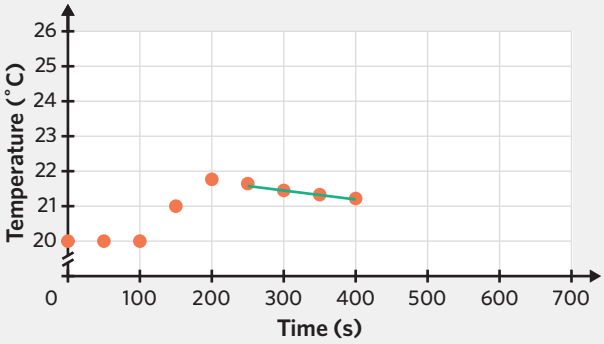
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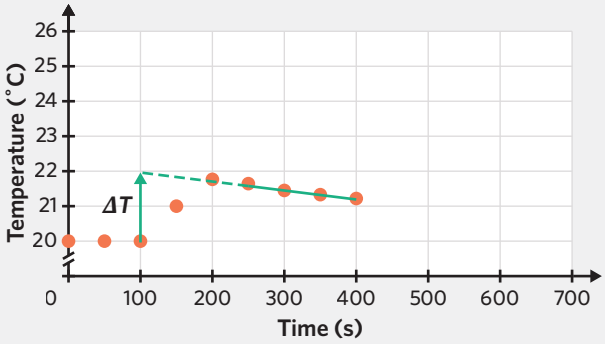
What strategies do we need in order to answer the question?

1. Extrapolate the temperature-time graph to determine ΔT for electrical calibration.
2. Calculate the amount of energy used in electrical calibration using $q = VIt$.
3. Calculate calibration factor for this calorimeter using $\text{CF} = \frac{q}{\Delta T}$.
4. Estimate the amount of energy released from ethanol combustion using $q = \text{CF} \times \Delta T$.
5. Convert energy values in J to kJ by dividing by 10^3.
6. Calculate molar heat of combustion using the formula molar heat of combustion of ethanol $= \frac{q}{n(\text{fuel})}$.

Answer

Draw a line to fit the points after the temperature begins decreasing. Then, extrapolate this line back to the point at which the heating element was switched on.





$\Delta T_{\text{calibration}} = 22.0\ ^\circ\text{C} - 20.0\ ^\circ\text{C}$

$\Delta T_{\text{calibration}} = 2.0\ ^\circ\text{C}$

$q = VIt$

$q = 5.0\ \text{V} \times 1.2\ \text{A} \times 100\ \text{s}$

$q = 600\ \text{J}$

$\text{CF} = \frac{q}{\Delta T}$

$\text{CF} = \frac{600\ \text{J}}{2.0\ ^\circ\text{C}}$

$\text{CF} = 300\ \text{J}\ ^\circ\text{C}^{-1}$

$q(\text{from ethanol}) = \text{CF} \times \Delta T_{\text{from ethanol}}$

$q(\text{from ethanol}) = 300\ \text{J}\ ^\circ\text{C}^{-1} \times 36.4\ ^\circ\text{C}$

$q(\text{from ethanol}) = 10\ 920\ \text{J}$

$q(\text{from ethanol}) = 10\ 920 \div 10^3\ \text{kJ}$

$q(\text{from ethanol}) = 10.920\ \text{kJ}$

$\text{molar heat of combustion of ethanol} = \frac{q}{n(\text{fuel})}$

$\text{molar heat of combustion of ethanol} = \frac{10.920\ \text{kJ}}{0.010\ \text{mol}}$

$\text{molar heat of combustion of ethanol} = 1092\ \text{kJ mol}^{-1}$

Therefore, the experimental value for ethanol's molar heat of combustion is $1.1 \times 10^3\ \text{kJ mol}^{-1}$ (2 sig. figs).

PROGRESS QUESTIONS

Question 4

A calorimeter can more accurately estimate the amount of heat energy released by

A. retaining energy in its walls.

B. reducing the amount of heat used to heat the surrounding air.

C. making the amount of heat loss more consistent and hence more measurable.

D. All of the above options correctly complete the statement.

Question 5

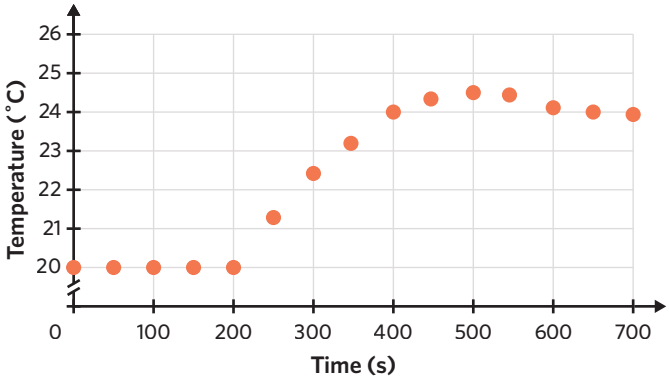
Han heats a quantity of water in a calorimeter for 150 seconds with a current of 1.3 A and a voltage of 6.0 V, causing the water temperature to rise by 2.1 °C.

The calibration factor for their calorimeter (in J °C^{-1}) is closest to

A. 19 J °C^{-1} **B.** 550 J °C^{-1} **C.** 560 J °C^{-1} **D.** 1200 J °C^{-1}

Question 6

A chemist electrically calibrates a calorimeter by turning the heater on for 200 seconds.



Using the more accurate extrapolation method, the value of ΔT for this experiment is

A. 4.0 °C **B.** 4.5 °C **C.** 5.5 °C **D.** 6.5 °C

Solution calorimetry 3.1.11.2

One major type of calorimetry is **solution calorimetry**. Although it cannot be used to measure the enthalpy change of combustion reactions, it is simple to implement and can be done without expensive apparatus.

How does a solution calorimeter work?

A solution calorimeter is used to measure the enthalpy change of reactions that occur in solution, particularly dissolution reactions, precipitation reactions, and neutralisation reactions. A diagram of a polystyrene solution calorimeter (a 'coffee cup calorimeter') is shown in figure 7. The stirrer ensures that the reaction mixture is homogeneous (i.e. evenly spread throughout the vessel).

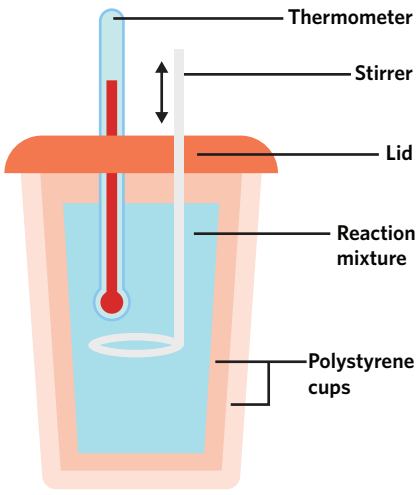


Figure 7 Solution calorimeter made using a polystyrene cup

Solution calorimeters can be used to measure the enthalpy change of either endothermic or exothermic reactions. For example, ammonium nitrate dissolves in water according to the equation

$NH_4NO_3(s) \rightarrow NH_4^+(aq) + NO_3^-(aq) \quad \Delta H > 0$

Since this endothermic reaction occurs in solution, its ΔH value could theoretically be estimated using a solution calorimeter.

PROGRESS QUESTIONS

Question 7

Solution calorimetry could be used to estimate the enthalpy change of which of the following reactions?

A. $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

B. $AgNO_3(aq) + HCl(aq) \rightarrow AgCl(s) + HNO_3(aq)$

C. $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

D. $MgCO_3(s) + 2HNO_3(aq) \rightarrow Mg(NO_3)_2(aq) + CO_2(g) + 2H_2O(l)$

Theory summary

- The specific heat capacity value of water, 4.18 J g^{-1} $°C^{-1}$, can be used in the equation $q = mc\Delta T$ to estimate the energy released from the combustion of fuels.
- A calorimeter is a reaction vessel designed to minimise heat loss to the environment.
- By comparing theoretical values with experimental values from a calorimetry experiment, a calibration factor for the experimental setup can be determined.
- Calibration factor (CF), usually measured in J $°C^{-1}$, can be used to much more accurately estimate the enthalpy change of a reaction, using the equation $q = CF \times \Delta T$. It can be calculated using electricity (using the formula $q = VIt$), or by comparison with a specific reaction of known enthalpy change.
- Temperature-time graphs can be used to represent the results of a calorimetry experiment and hence determine the calibration factor by extrapolation.
- Solution calorimetry is a specific type of calorimetry used to measure the enthalpy change of reactions occurring in solution.

2B Questions

Mild Medium Spicy

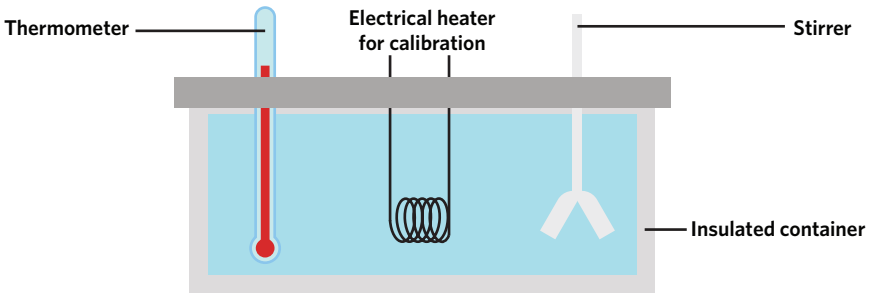
Deconstructed

Use the following information to answer questions 8–10.

Massimo devises a solution calorimetry experiment to determine the enthalpy change of the dissolution of sodium hydroxide pellets (NaOH) in water.

$NaOH(s) \rightarrow Na^+(aq) + OH^-(aq)$

A diagram of his calorimeter is shown.



To calibrate this calorimeter, he passes a current of 1.50 A through the electrical heater for 60.0 seconds with an applied voltage of 6.05 V. The water rises in temperature by 3.87 °C. Once the water has cooled back to its original temperature, he places 1.03 g of NaOH in the same calorimeter, causing a temperature rise of 8.02 °C.

Question 8 (1 MARK)

The amount (in mol) of NaOH that dissolved was

A. 0.02575 mol **B.** 0.04481 mol **C.** 0.06062 mol **D.** 1.030 mol

Question 9 (1 MARK)

The calibration factor for this calorimeter is closest to

A. 9.075 J °C^{-1} **B.** 135.8 J °C^{-1} **C.** 140.7 J °C^{-1} **D.** 544.5 J °C^{-1}

Question 10 (1 MARK)

Based on this experiment, the molar enthalpy change of the dissolution of NaOH is

A. −21.1 kJ mol^{-1}

B. −43.8 kJ mol^{-1}

C. 44.5 kJ mol^{-1}

D. 1.01×10^3 kJ mol^{-1}

Exam-style

Question 11 (4 MARKS)

Biogas was combusted to release 1.63×10^3 kJ of energy. This energy was used to heat 100 kg of water in a tank. The initial temperature of the water was 25.0 °C.

a. What is the maximum temperature that the water in the tank could reach? 3 MARKS

b. State why this temperature may not be reached. 1 MARK

VCAA 2021 exam Short answer Q1c

Question 12 (1 MARK)

Solution calorimetry would be **least** appropriate for which of the following reactions?

A. $Co(NO_3)_2(aq) + 2KOH(aq) \rightarrow 2KNO_3(aq) + Co(OH)_2(s)$

B. $NH_4Cl(s) \rightarrow NH_4^+(aq) + Cl^-(aq)$

C. $HNO_3(aq) + NaOH(aq) \rightarrow NaNO_3(aq) + H_2O(l)$

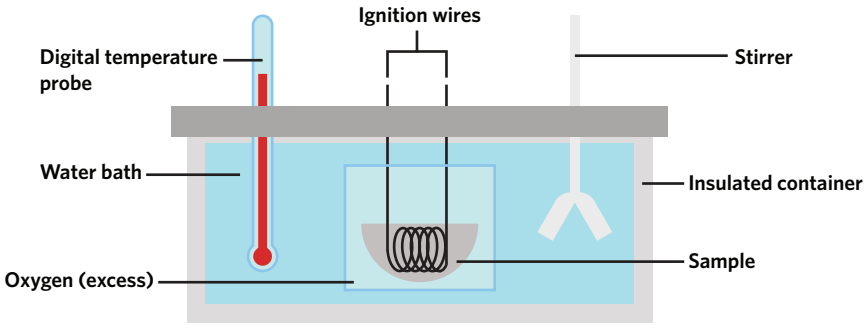
D. $2HCl(aq) + Fe(s) \rightarrow FeCl_2(aq) + H_2(g)$

Question 13 (3 MARKS)

One of the largest power surges in history occurred in Great Britain during halftime of the 1966 England vs West Germany FIFA World Cup final. Experts estimate that 1.00×10^3 GJ ($1 \text{ GJ} = 10^9$ J) of this energy was used to heat water in kettles. If the average kettle contains 1.50 kg of water and has its temperature increased by 75.0 °C when it is switched on, how many kettles were switched on at halftime?

Question 14 (7 MARKS)

The energy content of foods can be determined using a type of calorimeter known as a bomb calorimeter, similar to the one shown.



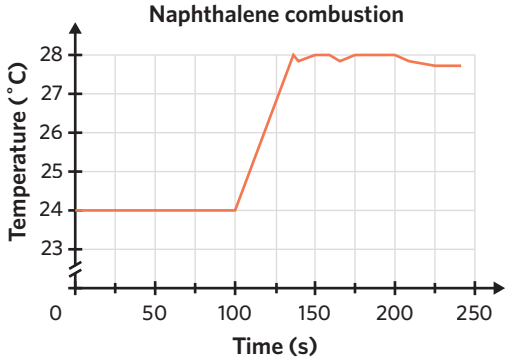
The calibration factor for the bomb calorimeter is initially determined by burning a known amount of naphthalene, $C_{10}H_8$. The combustion reaction for $C_{10}H_8$ is

$C_{10}H_8(s) + 12O_2(g) \rightarrow 10CO_2(g) + 4H_2O(l) \quad \Delta H = -5133 \text{ kJ mol}^{-1}$

Data for the calibration of the bomb calorimeter

Mass of $C_{10}H_8$	0.212 g
Mass of water	300 g

The graph produced by the digital temperature probe in the bomb calorimeter is shown below.



a. Explain why it is useful to calibrate a calorimeter. 2 MARKS

b. Use the data to calculate the calibration factor for this calorimeter. 4 MARKS

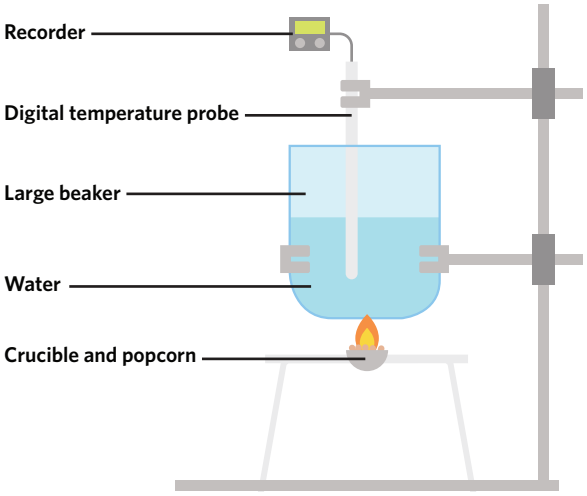
VCAA (NHT) 2018 Short answer Q6ai

c. A corn chip contains 51.8 kJ of energy. If a corn chip were completely combusted in this calorimeter, by how much would the water's temperature be expected to rise? 1 MARK

Key science skills

Question 15 🌶🌶🌶 (9 MARKS)

A brand of air-popped popcorn has an energy density of 16.3 kJ g^{-1}. An experiment was carried out to determine this value experimentally. The apparatus is shown, where the beaker contains 500.0 g of water.



a. A 1.52 g sample of air-popped popcorn is completely combusted, causing the water's temperature to rise by 1.1 °C. Using this method, calculate the energy released by the air-popped popcorn in kilojoules per gram. 2 MARKS

b. A student was not convinced by the results of this method, and decided to use calorimetry instead. A 1.50 g sample of air-popped popcorn was placed in a metal calorimeter with a calibration factor of 6.54 kJ $°C^{-1}$. This popcorn sample was combusted, causing the water temperature to rise from 22.2 °C to 25.7 °C. Using the calibration factor provided, calculate the energy released by the air-popped popcorn in kilojoules per gram. 2 MARKS

c. A key goal for scientists is accuracy.

i. Justify which of the two methods produced a more accurate result. 1 MARK

ii. State two major reasons why a more accurate result was obtained from this method. 2 MARKS

d. Consider the value obtained in part **b** in comparison with popcorn's theoretical energy density. Assume that the calorimeter is accurately calibrated and that the calibration factor accounts for all heat loss. State **two** factors that may contribute to any disparity. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q6

FROM LESSONS 12B & 12D

Questions from multiple lessons

Question 16 🌶🌶🌶 (4 MARKS)

0.500 g of ethane gas, C_2H_6, undergoes complete combustion in a calorimeter containing 200.0 mL of water. The water temperature rises from 22.0 °C to 48.5 °C. What is the thermochemical equation for the combustion of C_2H_6 using this information? Assume that the calorimeter is perfectly insulated, and that the density of water is 1.00 g mL^{-1}.

Adapted from VCAA (NHT) 2019 Exam Multiple choice Q23

FROM LESSON 1D

Question 17 🌶🌶🌶 (6 MARKS)

Romy's local petrol station advertises that its LPG is 'pure propane', but she hypothesises that this is untrue. To test this hypothesis, she purchases a 0.196 L sample of gaseous LPG from the petrol station, and combusts it, at SLC, in a calorimeter that she knows has a calibration factor of 833 J $°C^{-1}$. Her results were as follows:

Volume of LPG combusted (L)	0.196
Initial mass of water in calorimeter (g)	200.0
Final mass of water in calorimeter (g)	200.0
Initial temperature of water in calorimeter (°C)	25.0
Final temperature of water in calorimeter (°C)	46.0

a. Using data from the VCE Data Book, write a balanced thermochemical equation for the complete combustion of propane. 2 MARKS

b. Assuming that the calibration factor is accurate and combustion occurs completely, do Romy's results support her hypothesis? Justify your answer using calculations. 4 MARKS

FROM LESSONS 1D & 2A

Back to contents

2C Energy from fuels and food

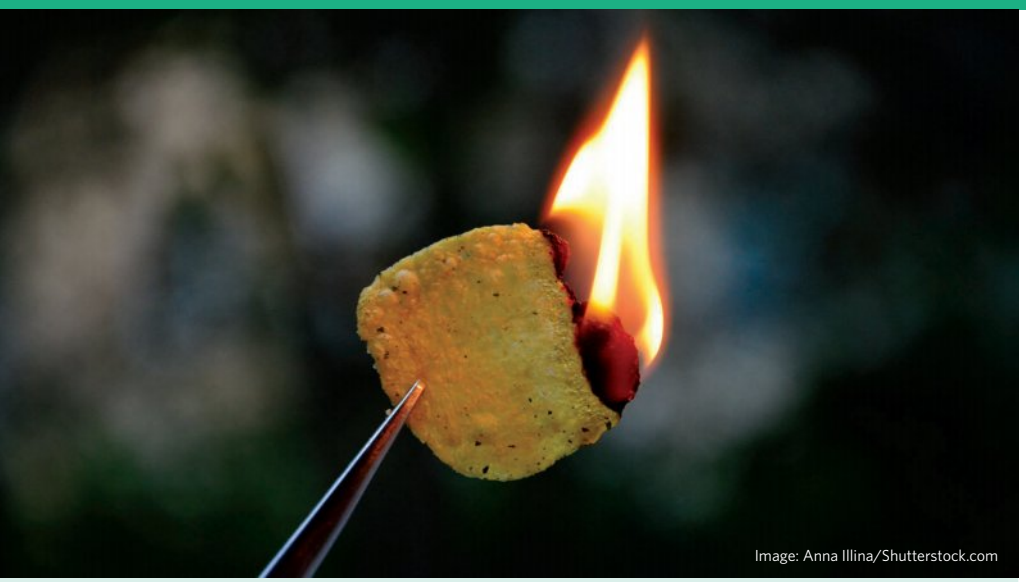


Image: Anna Illina/Shutterstock.com

What contains more energy: a kilogram of petrol or a kilogram of corn chips?

Fuels are not just organic chemicals used in motor vehicles; since all foods contain energy, they are fuels, too. In fact, some high-energy foods, such as flavoured corn chips, have a comparable energy content to transport fuels. In this lesson, we will explore how to quantify the energy efficiency of combustion reactions of fuels and foods, as well as how to use the nutrient content of foods to determine their total energy content.

KEY TERMS AND DEFINITIONS

Energy transformation conversion of energy from one form (such as chemical, electrical, kinetic, thermal, light, or sound) to another

Percentage efficiency percentage of energy transformed to a 'useful' form or transferred to a substance

Useful energy proportion of total energy that can be used for the desired purpose

STUDY DESIGN DOT POINT

- energy from fuels and food:
  - calculation of energy transformation efficiency during combustion as a percentage of chemical energy converted to useful energy
  - comparison and calculations of energy values of foods containing carbohydrates, proteins and fats and oils

2A 2B 2C

3.1.12.1 Energy efficiency of combustion reactions

3.1.12.2 Comparison and calculations of energy in foods

ESSENTIAL PRIOR KNOWLEDGE

1C Fuel for the body

2B Energy absorbed by water

See questions 14–15.

Energy efficiency of combustion reactions 3.1.12.1

As was explored in lesson 2B, in a water-heating experiment, not all energy from a combustion reaction goes towards heating the water; a large percentage is used to heat the beaker, the surrounding air, or to produce light. This same principle applies to any combustion reaction, be it in a car engine or in our bodies: not all energy is available in a 'useful' form.

How can we calculate the efficiency of combustion reactions?

A combustion reaction involves an **energy transformation** of chemical energy stored in a fuel or food primarily into thermal energy (heat). However, some of this energy is transferred to other objects and to the surrounding air, or transformed into less useful forms such as light or sound energy.

We are usually interested in the amount of **useful energy** produced: energy that can be used for the intended purpose (e.g. moving a car or maintaining human body temperature) and its quantity measured.

If the theoretical quantity of energy produced or the heat of the combustion of a reaction is known, and the amount of energy transformed into a useful form is measured, the **percentage efficiency** of the energy transformation during combustion can be calculated using the following formula.

$$\%\ \text{energy efficiency} = \frac{\text{actual or experimental value (e.g. useful energy output)}}{\text{theoretical value (e.g. chemical energy input)}} \times 100\%$$

The experimental and theoretical values can be values of almost any quantity – total energy, energy per gram, or even a mass of fuel required to produce a given amount of energy – as long as both the experimental and theoretical values are of the same type and units.

For example, if the combustion of a fuel for a camping stove should theoretically produce 100 kJ of energy, but only 70 kJ of energy is actually absorbed by the water on the stove in an experiment, this reaction is 70% efficient.

$$\%\ \text{energy efficiency} = \frac{\text{actual or experimental value}}{\text{theoretical value}} \times 100\%$$

$$\%\ \text{energy efficiency} = \frac{70\ \text{kJ}}{100\ \text{kJ}} \times 100\%$$

$$\%\ \text{energy efficiency} = 70\%$$

Digestion in the human body, though very efficient, is not 100% efficient; one source of energy loss is dietary fibre, a carbohydrate that humans cannot digest or absorb energy from. Figure 1 illustrates the energy transformations and respective efficiencies in a combustion engine, whereas figure 2 illustrates the various energy conversions associated with digestion of foods in the human body. Efficiency (atom economy) of multi-stage reactions will be explored further in lesson 8B.

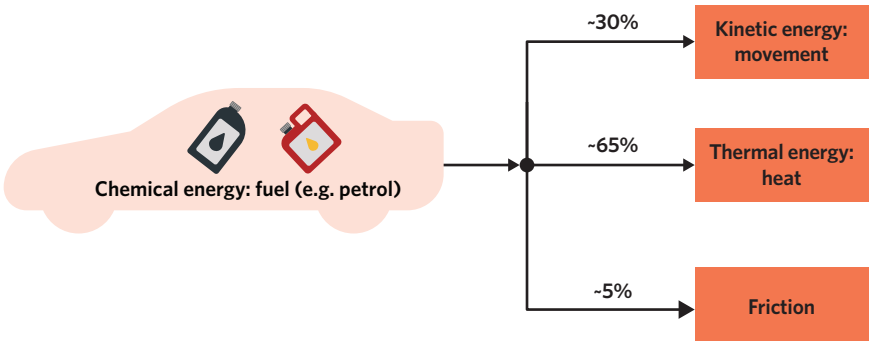


Figure 1 Energy conversions and efficiencies in the combustion engine of a motor vehicle

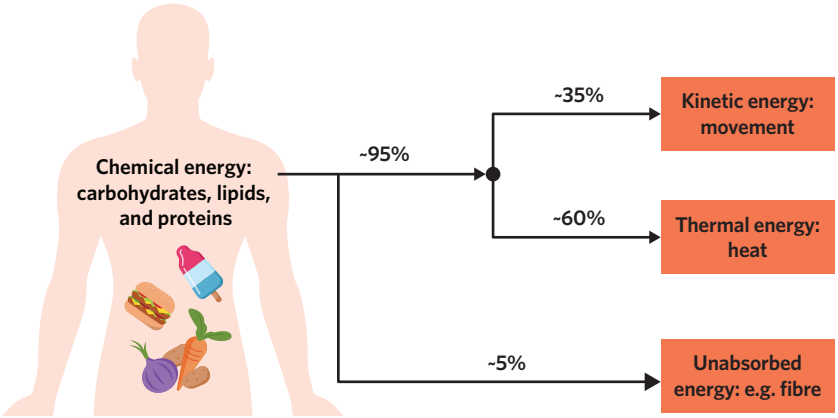


Figure 2 Energy conversions and efficiency in the human body

USEFUL TIP

The % energy loss of a reaction can be calculated using the formula

% energy loss = 100% − % energy efficiency

Equivalently, % energy efficiency can be calculated as

% energy efficiency = 100% − % energy loss

WORKED EXAMPLE 1

An efficient combustion engine in a motor vehicle loses 61% of its energy input. To drive 1 km, the engine needs to output 180 kJ of energy. What mass (in grams) of petrol must be input for the engine to output 180 kJ of energy? Assume that the petrol used is pure octane (C_8H_{18}).

What information is presented in the question?

The % heat loss of the energy transformation in the combustion engine is 61%.

The fuel used is pure octane (C_8H_{18}).

The engine has an energy output of 180 kJ.

What is the question asking us to do?

Calculate the mass (in g) of octane required by this engine to output 180 kJ of energy.

What strategies do we need in order to answer the question?

1. Calculate the % efficiency of the engine using the % heat loss.
2. Calculate the required energy input using the efficiency and energy output.
3. Use the VCE Data Book to determine the heat of combustion of the fuel.
4. Calculate the required mass of fuel using the required energy input.

Answer

% energy efficiency = 100% − % energy loss

% energy efficiency = 100% − 61%

% energy efficiency = 39%

energy efficiency = 0.39

$$\text{required energy input} = \frac{\text{energy output}}{\text{energy efficiency}}$$

$$\text{required energy input} = \frac{180\text{ kJ}}{0.39}$$

required energy input = 461.54 kJ

From the VCE Data Book, heat of combustion of $C_8H_{18} = 47.9\text{ kJ g}^{-1}$

$$\text{required } m(C_8H_{18}) = \frac{\text{required energy input}}{\text{heat of combustion of } C_8H_{18}}$$

$$\text{required } m(C_8H_{18}) = \frac{461.54\text{ kJ}}{47.9\text{ kJ g}^{-1}}$$

required $m(C_8H_{18})$ = 9.6 g (2 sig. figs)

PROGRESS QUESTIONS

Question 1

Percentage energy efficiency for combustion is the percentage of

A. thermal energy converted to chemical energy.

B. useful energy converted to chemical energy.

C. thermal energy converted to useful energy.

D. chemical energy converted to useful energy.

Question 2

A cereal product is claimed to contain 459 kJ of energy per serve. When combusted in an insulated metal container, 288 kJ of energy is transferred to a vessel of water as heat. What is the percentage efficiency of this energy transformation?

A. 0.373%

B. 37.3%

C. 62.7%

D. 159%

Comparison and calculations of energy in foods 3.1.12.2

The nutritional information panels on food packaging provide values for the amount of energy present, usually per serving and per 100 g of the foodstuff. These values can be estimated based on the quantities of certain nutrients in the food.

How can we calculate the amount of energy in foods?

In lesson 1C, we discussed foods as fuels for the body.[1] Carbohydrates and lipids (fats and oils) are two components of food which are constantly broken down by the body to produce energy, whereas proteins can also be used as an energy source if the body has exhausted all other sources of energy. The average amount of energy produced from combustion of 1 gram of each of these nutrients is shown in table 1.

KEEN TO INVESTIGATE?

1 **Does eating energy-dense food make you feel fuller?**
Search YouTube: Does energy density matter for satiety?

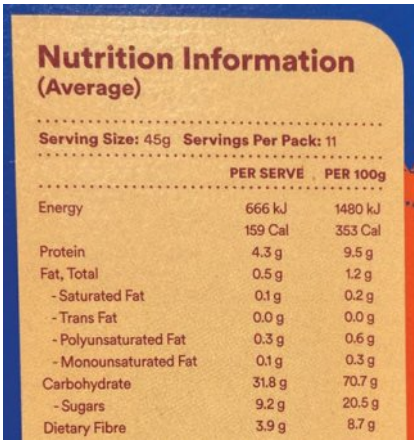


Figure 3 Nutrition information for a fruit cereal

Table 1 Energy content of nutrients

Food	Heat of combustion (kJ g^{-1})
Fats and oils	37
Protein	17
Carbohydrate	16

USEFUL TIP

The values for the heat of combustion of different nutrients are given in the VCE Data Book to 2 significant figures, which means that for questions involving calculation of total energy in a food sample, answers are usually to be given to a maximum of 2 significant figures.

If we know the respective masses of fats and oils, proteins, and carbohydrates present in a food sample – such as by using the nutritional information on the packaging (figure 3) – we can calculate the theoretical quantity of energy that could be obtained from each nutrient, using the following formula.

Energy from nutrient = mass of nutrient in sample × heat of combustion of nutrient

Then, we can estimate the total amount of energy present in the sample by taking the sum of the energy values for each nutrient as follows.

Total energy in sample = energy from fats or oils + energy from protein + energy from carbohydrates

MISCONCEPTION

'Protein is a major energy source for humans.'

Although protein contains energy, carbohydrates and fats provide the vast majority of energy to humans on a daily basis. Protein is primarily used to replace muscle and to grow, and is only used for energy if the body has used up all carbohydrate and fat stores, such as towards the end of a marathon.

WORKED EXAMPLE 2

The nutritional value of a homemade muesli is shown.

Nutrient	Amount per 100 g
Fats	23 g
Total carbohydrates	23 g
Proteins	9.0 g
Fibre	11 g

Calculate the energy, in kJ, of energy provided by the consumption of 100 g of the muesli.

What information is presented in the question?

The mass of different nutrients in a muesli.

What is the question asking us to do?

Calculate the amount of energy in 100 g of the muesli.

What strategies do we need in order to answer the question?

1. Calculate the energy provided by each major nutrient.
2. Add the values together to determine the overall amount of energy in 100 g of the muesli.

Answer

Fibre provides no energy to humans, so is not included in calculations.

energy provided by fats = 23 g × 37 kJ g^{-1}

energy provided by fats = 851 kJ

energy provided by carbohydrates = 12 g × 16 kJ g^{-1}

energy provided by carbohydrates = 192 kJ

energy provided by proteins = 9.0 g × 17 kJ g^{-1}

energy provided by proteins = 153 kJ

total energy provided = energy from fats + energy from carbohydrates + energy from proteins

total energy provided = 851 kJ + 192 kJ + 153 kJ

total energy provided = 1196 kJ

total energy provided = 1.2×10^3 kJ (2 sig. figs)

PROGRESS QUESTIONS

Question 3

The nutritional information for one medium serving (124 g) of sweet potato is provided in the table below.

Nutrient	Per 124 g
Protein	2.0 g
Fat	3.0 g
Carbohydrates	18.7 g

The energy contained in one medium serving of sweet potato is closest to

A. 3.6×10^2 kJ

B. 4.2×10^2 kJ

C. 4.4×10^2 kJ

D. 5.5×10^2 kJ

Adapted from VCAA 2021 exam Short answer Q5a

Theory summary

- The actual energy available from combustion reactions is often less than theoretical values indicate due to heat lost to the environment.
- The % energy efficiency of combustion reactions can be calculated as $\frac{\text{actual energy available}}{\text{theoretical energy produced}} \times 100\%$
- The values for energy content (in kJ g^{-1}) of proteins, lipids (fats and oils), and carbohydrates (excluding fibre) can be used to calculate the total estimated energy content of foods.

2C Questions

Mild Medium Spicy

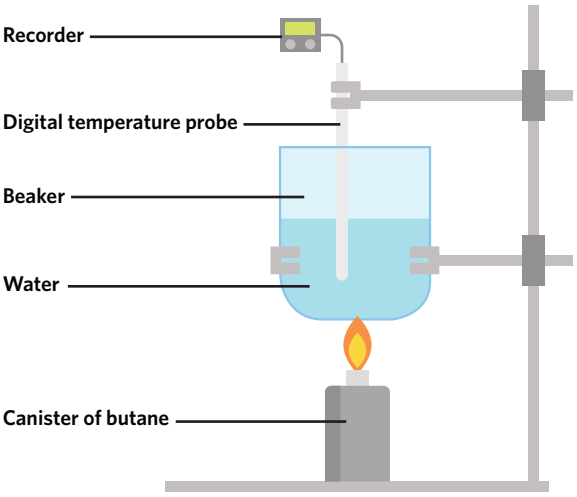
Deconstructed

Use the following information to answer questions 4–6.

Callista devises an experiment to estimate the heat of combustion of butane, and wants to know the energy efficiency of her experimental setup shown.

Initial mass of canister and butane (g)	60.84
Final mass of canister and butane(g)	59.16
Mass of empty canister (g)	56.69

Mass of water (g)	100.0
Initial temperature of water (°C)	22.14
Final temperature of water (°C)	39.40
Theoretical energy density of butane (kJ g^{-1})	49.7



Question 4 (1 MARK)

The mass of butane combusted in this experiment was

A. 0.79 g **B.** 1.68 g **C.** 2.47 g **D.** 4.15 g

Question 5 (1 MARK)

The theoretical amount of energy released by the butane combusted is closest to

A. 7.21 kJ **B.** 49.7 kJ **C.** 83.5 kJ **D.** 99.4 kJ

Question 6 (3 MARKS)

By comparing theoretical and experimental values, calculate the percentage energy efficiency of Callista's experimental setup.

Exam-style

Question 7 (2 MARKS)

The table below shows nutritional information for the edible flesh of an avocado.

Nutrient	**Amount per 100 g of edible flesh of an avocado**
Total carbohydrates, including: *Total digestible carbohydrates*	8.5 g *1.8 g*
Protein	2.0 g
Water	73.2
Fats	14.7 g

Calculate the energy released when 100 g of avocado is digested.

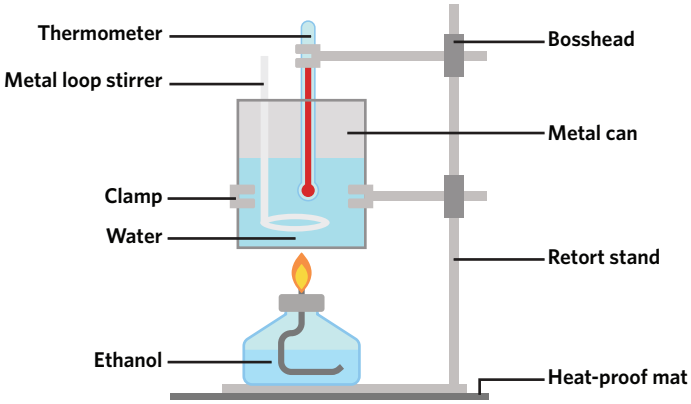
VCAA (NHT) 2022 exam Short answer Q1b

Question 8 (5 MARKS)

The enthalpy for the combustion of ethanol is provided in the VCE Data Book. This combustion of ethanol is represented by the following equation.

$C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

A spirit burner used 1.80 g of ethanol to raise the temperature of 100.0 g of water in a metal can from 25.0 °C to 40.0 °C.



a. Calculate the percentage of heat lost to the environment and to the apparatus. 4 MARKS

b. Identify **one** way to limit heat loss to the environment. 1 MARK

VCAA 2014 Exam 2 Short answer Q3a,b

Question 9 (5 MARKS)

Penny wanted to develop a new 'high protein, low carbohydrate' snack bar that contains **less than** 800 kJ of energy.

For their first batch of snack bars, they included **only** the following ingredients in each bar:

Ingredient	Amount (g)
Protein powder (protein)	9.8
Flour (carbohydrate)	20.0
Fibre mix (fibre)	3.2
Butter (fat)	7.0

a. Determine whether or not this mixture of ingredients would allow the bar to meet Penny's energy requirements. 2 MARKS

b. According to food regulations, all food products need to have their energy content expressed as kJ/100 g. Determine the energy content of the bar in kJ/100 g. 2 MARKS

c. What percentage of the bar's energy is provided by the butter? 1 MARK

Question 10 (3 MARKS)

A granola bar is confirmed to contain 1022.7 kJ of energy per serving.
As part of its advertising, the company claims that the bar contains more than 5 g of protein.

Given that the bar contains 21.3 g of carbohydrates and 16.5 g of fat per serving, determine the accuracy of the claim made by the company.

Question 11 (1 MARK)

1 L of octane has a mass of 703 g at SLC. The efficiency of the reaction when octane undergoes combustion in the petrol engine of a car is 25.0%. What volume of octane stored in a petrol tank at SLC is required to produce 528 MJ (1 MJ = 10^6 J) of usable energy in a combustion engine?

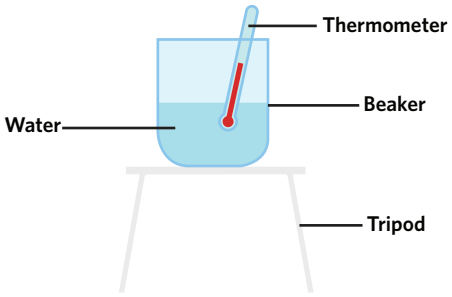
A. 3.92 L **B.** 11.8 L **C.** 15.7 L **D.** 62.7 L

VCAA 2021 exam Multiple choice Q22

Key science skills

Question 12 (7 MARKS)

Corn can be made into ethanol, or into corn chips, both of which can be used as fuel. Rui wants to determine which of these contains more energy per gram. They set up the partial apparatus shown.



a. State what additional apparatus and method could be used to experimentally determine the heat of combustion of

i. ethanol. 1 MARK

ii. corn chips. 1 MARK

b. Identify **one** safety risk associated with your chosen method for

i. ethanol. 1 MARK

ii. corn chips. 1 MARK

c. The nutritional information for the corn chips Rui uses is given.

Nutrient	Quantity per 100 g
Protein	6.3 g
Fat, total	26.6 g
Carbohydrate	59.4 g
Sodium	330 mg

Determine theoretically whether ethanol or corn chips contain more energy per 100 g. 3 MARKS

FROM LESSON 12B

Questions from multiple lessons

Question 13 (3 MARKS)

Cellular respiration is an important process that supplies energy for the body.

a. Give the balanced equation for cellular respiration. 1 MARK

b. If 4.3 g of glucose in food were consumed, how much energy would be produced during cellular respiration? Assume 100% efficiency. 2 MARKS

FROM LESSON 1C

Question 14 (7 MARKS)

A pair of students use a Bunsen burner to heat a beaker containing 350.0 g of water. Complete combustion of 0.485 g of CH_4 raises the temperature of the water from 20 °C to 32.3 °C.

a. Calculate the percentage of the Bunsen burner's energy that is absorbed by the water. 3 MARKS

Adapted from VCAA 2020 exam Short answer Q6c

b. The students are given another fuel with an unknown heat of combustion. Since they do not have access to a calorimeter, the students must use this same setup to estimate the fuel's heat of combustion.

i. Explain why the students would likely obtain an inaccurate result. 1 MARK

ii. Applying the principles of calorimetry, suggest an experimental method the students could use with the same setup to obtain a significantly more accurate estimate of the unknown fuel's heat of combustion. 3 MARKS

FROM LESSON 2B

Chapter 2 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

A fruitcake is claimed to contain 45% carbohydrates per 100 g serving by mass. The total energy provided by carbohydrates in a 100 g serving is closest to

A. 7.2 kJ **B.** 45 kJ **C.** 720 kJ **D.** 1600 kJ

Use the following information to answer questions 2–3.

A solution calorimeter containing 100.0 g of water is electrically calibrated using an applied voltage of 3.8 V and a current of 1.8 A for 200 seconds. The temperature change of the water was measured, and the calibration factor was determined to be 760 J $°C^{-1}$.

Question 2 (1 MARK)

The theoretical amount of heat released into the water during electrical calibration is closest to

A. 360 kJ **B.** 680 J **C.** 1400 kJ **D.** 1400 J

Question 3 (1 MARK)

In this calorimeter, 0.50 mol of NaOH is dissolved in the water, causing the water temperature to increase by 29.6 °C. The estimated enthalpy change of the dissolution of NaOH is closest to

A. -45 kJ mol^{-1} **B.** -22 kJ mol^{-1} **C.** $+22$ kJ mol^{-1} **D.** $+45$ kJ mol^{-1}

Question 4 (1 MARK)

A popular chocolate bar's nutritional information is shown in the table provided.

Nutrient	**Amount (g) per serving*** *serving size: 50 g
Protein	3.3
Fat (total)	12.9
Carbohydrates (digestible)	29.2
Sodium	0.14

Given that Rajesh ate 50 g of the chocolate bar, the energy in the chocolate Rajesh ate is closest to

A. 500 kJ **B.** 1000 kJ **C.** 1500 kJ **D.** 2000 kJ

Use the following information to answer questions 5–6.

In an experiment, when 3.00 g of ethanol in a spirit burner was combusted, it caused the temperature of 100.0 g of water, initially at 20.6 °C, to increase. From this, ethanol's heat of combustion was experimentally determined to be 3.02 kJ g^{-1}.

Question 5 (1 MARK)

What was the final temperature of the water?

A. 21.7 °C

B. 27.8 °C

C. 42.3 °C

D. 233 °C

Question 6 (1 MARK)

The percentage efficiency of the energy transfer to the water is closest to

A. 3.4% **B.** 10.2% **C.** 89.8% **D.** 110%

Question 7 (1 MARK)

Compared with measuring the temperature change of water in a glass beaker, measuring the temperature change in a well-insulated calorimeter and using a calibration factor generally lead to

A. more accurate and more precise results.

B. more accurate but less precise results.

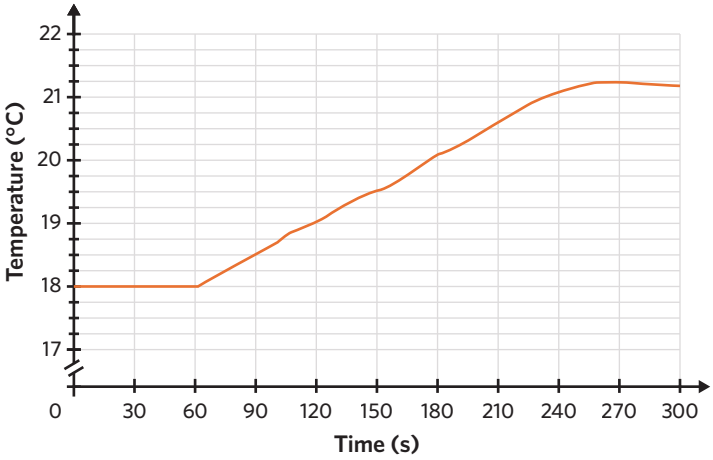
C. less accurate but more precise results.

D. less accurate and less precise results.

Use the following information to answer questions 8–9.

A solution calorimeter containing 350 mL of water was set up. The calorimeter was calibrated electrically and the graph of the results is shown.

Graph of temperature versus time during electrical calibration of solution calorimeter



The calorimeter was calibrated using a current of 2.7 A, starting at 60 s. The current was applied for 180 s and the applied voltage was 5.4 V.

Question 8 (1 MARK)

The calibration factor for this calorimeter is closest to

A. 125 J $°C^{-1}$

B. 820 J $°C^{-1}$

C. 847 J $°C^{-1}$

D. 875 J $°C^{-1}$

VCAA 2020 exam Multiple choice Q9

Question 9 (1 MARK)

This type of calorimeter

A. has no heat loss.

B. can be used for combustion reactions.

C. requires electrical calibration in order to determine the calibration factor.

D. can be used for multiple reactions without recalculating the calibration factor.

Adapted from VCAA 2020 exam Multiple choice Q10

Question 10 (1 MARK)

Ammonium nitrate, NH_4NO_3, can be used in chemical cold packs that are often found in first-aid kits.

A calorimeter was electrically calibrated using 100 mL of pure water and was then used to determine the molar heat of solution of NH_4NO_3 (the amount of energy absorbed per mole of NH_4NO_3 dissolved).

If the water was replaced prior to determination of the molar heat of solution and, instead of 100 mL, only 90 mL was added to the calorimeter, the molar heat of solution determined would be

A. lower due to the temperature change being smaller.

B. lower due to the temperature change being greater.

C. higher due to the temperature change being smaller.

D. higher due to the temperature change being greater.

VCAA (NHT) 2021 exam Multiple choice Q7

Short answer (30 MARKS)

Question 11 (10 MARKS)

Ethyne, C_2H_2, is a chemical compound that can be used as a fuel. A calorimetry experiment determines that the complete combustion of ethyne at SLC releases 1300 kJ of energy per mole of ethyne combusted.

a. Write the balanced thermochemical equation for the complete combustion of C_2H_2 at SLC (the boiling point of ethyne is −84 °C). 2 MARKS

b. How many moles of carbon dioxide, CO_2, are produced when 200.0 L of C_2H_2 is completely combusted at SLC? 2 MARKS

c. What mass of C_2H_2, in kilograms, will produce 25 MJ of energy when completely combusted at SLC (1.0 MJ = 1.0×10^3 kJ)? 2 MARKS

d. 112.5 kJ of energy is absorbed by 500.0 mL of water when an amount of C_2H_2 is combusted (density of water = 0.997 g mL^{-1}). The water was initially at SLC. What is the temperature of the water after the combustion energy is absorbed? 4 MARKS

VCAA (NHT) 2022 exam Short answer Q4

Question 12 (4 MARKS)

There are many varieties of bread available to consumers in Australia. The nutritional values for one type of wholemeal bread are given in the table.

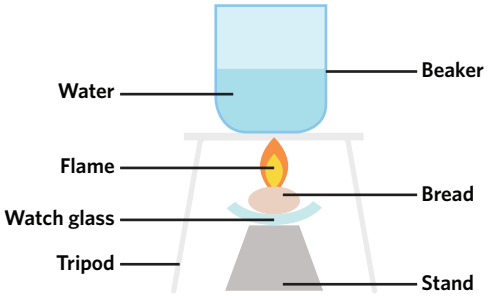
	Per 100 g
Energy	1000 kJ
Protein	9.1 g
Fats and oils	2.5 g
Carbohydrates	41.5 g
Sugars	3.0 g
Fibre	6.4 g

a. Calculate the energy, in kilojoules, provided by the protein and fats and oils in 100 g of this wholemeal bread. 1 MARK

b. The wholemeal bread undergoes complete combustion in a calorimeter containing 200 g of water. Assume that all of the energy in the combustion is transferred to the water.

i. Calculate the mass of bread needed to raise the temperature of the water by 6 °C. 2 MARKS

ii. The combustion of the bread was investigated using a different method. The bread was ignited under a beaker containing 200 g of water, which was set on a tripod. The equipment used is shown in the diagram provided.



If 1.2 g of bread was needed to raise the temperature of the water by 6.0 °C using this different method, calculate the efficiency of the energy transfer in this combustion. 1 MARK

VCAA 2019 exam Short answer Q6a, f

Question 13 🌶🌶🌶 (3 MARKS)

The table provided shows the amount of each nutrient in 100 g of banana.

An athlete uses 300 kJ of energy for a five-minute run. A typical ripe banana has an average mass of 116 g after it is peeled.

How many typical ripe bananas, correct to two decimal places, would the athlete need to consume to replace the energy used during the run? Show your working.

Nutrient	Per 100 g
Protein	1.1 g
Carbohydrates	22.8 g
Fat	0.30 g

VCAA 2020 exam Short answer Q5c

Question 14 🌶🌶🌶 (3 MARKS)

A student aims to calculate the theoretical amount of energy available to the body from cellular respiration using the oxygen gas, O_2, retained by the body in a normal breath.

In this calculation, the student assumes that:

- The energy released at normal body temperature is the same as that released at standard laboratory conditions (SLC).
- 19.6 mL of O_2 is retained by the body in a normal breath.

A balanced thermochemical equation for cellular respiration, with glucose as the primary reactant, is shown.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad \Delta H = -2816 \text{ kJ mol}^{-1}$$

What is the theoretical amount of energy produced through cellular respiration from the O_2 retained by the body in a normal breath?

Adapted from VCAA (NHT) 2019 exam Multiple choice Q25

Question 15 🌶🌶🌶 (3 MARKS)

The composition of two savoury biscuits is shown in the table.

Nutrient	Biscuit 1 (per 50 g)	Biscuit 2 (per 50 g)
Carbohydrates (total, **including** indigestible dietary fibre)	22.0 g	22.0 g
Protein	6.8 g	7.3 g
Fats	18.7 g	19.1 g
Dietary fibre	2.5 g	1.6 g

Which of the two biscuits contains more energy per serving? Assume each serving size is 50 g and justify your answer with calculations.

Question 16 (7 MARKS)

A model car manufacturer develops an internal combustion engine that uses gaseous butane as fuel. A full tank of fuel for this engine has a capacity of 80.0 L. Under the conditions inside this engine, butane combusts according to the following thermochemical equation.

$2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(l) \quad \Delta H = -5750 \text{ kJ}$

a. Calculate the volume of greenhouse gases produced when a full tank of fuel is combusted. 2 MARKS

b. Calculate the mass of water produced when a full tank of fuel is combusted. 3 MARKS

c. If the combustion of a full tank of fuel produces 5.0×10^3 kJ of useful energy, calculate the percentage energy efficiency of this engine. 2 MARKS

Key science skills (10 MARKS)

Question 17 (10 MARKS)

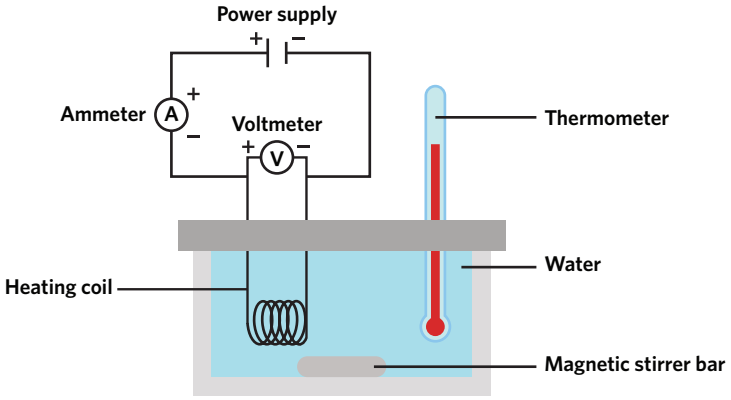
A chemistry class conducted a practical investigation to determine the calibration factor of a calorimeter using two different methods: electrical and chemical. Each student compared the results from the two different methods and presented the investigation as a scientific poster.

The materials, set-up and methods used by the students are shown.

Materials

- Calorimeter
- DC power supply
- 5 × wire leads
- Thermometer
- Stopwatch
- Ammeter
- Voltmeter
- Electronic balance
- Measuring cylinder
- 3 g of potassium nitrate (KNO_3)

Calorimeter setup



Methods

Electrical method for collecting calibration data:

1. Add 100 mL of water to the calorimeter. Stir the water and record its temperature every 30 seconds for several minutes.
2. Apply a voltage of 6 V for three minutes. Stir throughout and record the temperature every 30 seconds.
3. Record the voltage and the current while the water is heating.
4. Once the power is turned off, continue to stir the water and record the temperature every 30 seconds for a further three minutes.

Chemical method for collecting calibration data:

1. Measure 3.0 g of KNO_3 accurately.
2. After completing the electrical calibration, add the KNO_3 to the calorimeter.
3. Stir and record the temperature every 30 seconds.

A student wrote the following aim.

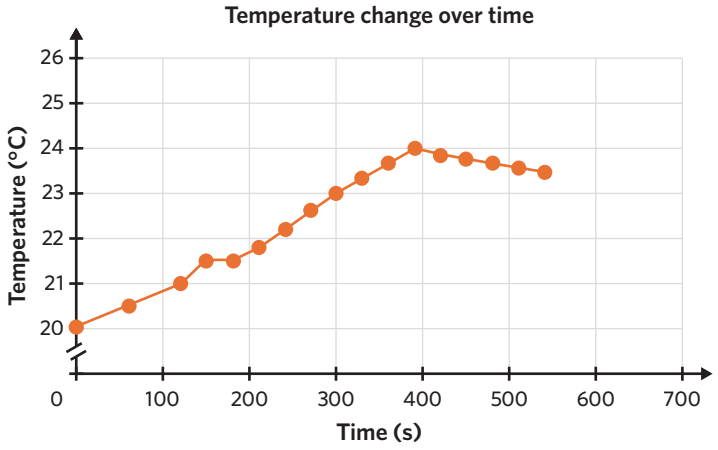
Aim
To compare the calibration factors obtained from two different methods.

The calibration factors were found by recording the temperature change of a solution resulting from the addition of a measured electrical input and from potassium nitrate dissolving in water.

a. The dependent variable in this investigation is the calibration factor. Identify the independent variable from the student's aim. 1 MARK

b. Identify **one** systematic error that applies **only** to the electrical method of calibration. 1 MARK

c. A student prepared the following graph for the temperature change during electrical calibration.



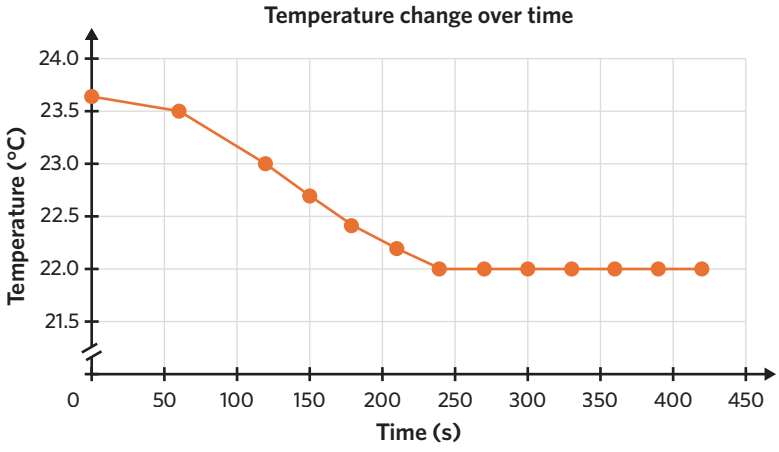
With respect to the outlined method, identify **one** issue with the student's graph. 1 MARK

d. Identify **one** limitation of the chemical method of calibration, as given in the 'Methods' section, and suggest how this could be addressed. 2 MARKS

e. A student's data for the chemical method of calibration is shown in the graph.

Results – Chemical method of calibration
Below is the chemical equation and enthalpy used to calculate the calibration factor for the chemical method.

$$KNO_3(s) \xrightarrow{H_2O} K^+(aq) + NO_3^-(aq) \quad \Delta H = +35 \text{ kJ mol}^{-1}$$



Use this data to calculate the calibration factor, in J $°C^{-1}$, for the chemical method of calibration. 3 MARKS

f. Another student suggests using the calibration factor calculated in part **e** to estimate the heat of combustion of propan-1-ol. Explain two issues with this suggestion. 2 MARKS

Adapted from VCAA 2018 exam Short answer Q9

FROM LESSONS 12C, 12D & 12E

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3

CHAPTER 3

Primary galvanic cells and fuel cells as sources of energy

LESSONS

3A Redox reactions

3B Writing redox equations

3C Primary galvanic cells

3D Designing galvanic cells

3E Fuel cells

3F Faraday's Laws in galvanic and fuel cells

3G Fuel cell challenges and innovations

Chapter 3 review

KEY KNOWLEDGE

- redox reactions as simultaneous oxidation and reduction processes, and the use of oxidation numbers to identify the reducing agent, oxidising agent and conjugate redox pairs
- the writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions
- the common design features and general operating principles of non-rechargeable (primary) galvanic cells converting chemical energy into electrical energy, including electrode polarities and the role of the electrodes (inert and reactive) and electrolyte solutions (details of specific cells not required)
- the use and limitations of the electrochemical series in designing galvanic cells and as a tool for predicting the products of redox reactions, for deducing overall equations from redox half-equations and for determining maximum cell voltage under standard conditions
- the common design features and general operating principles of fuel cells, including the use of porous electrodes for gaseous reactants to increase cell efficiency (details of specific cells not required)
- the application of Faraday's Laws and stoichiometry to determine the quantity of galvanic or fuel cell reactant and product, and the current or time required to either use a particular quantity of reactant or produce a particular quantity of product
- contemporary responses to challenges and the role of innovation in the design of fuel cells to meet society's energy needs, with reference to green chemistry principles: design for energy efficiency, and use of renewable feedstocks

Image: Kaca Skokanova/Shutterstock.com

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3A Redox reactions

STUDY DESIGN DOT POINT

- redox reactions as simultaneous oxidation and reduction processes, and the use of oxidation numbers to identify the reducing agent, oxidising agent and conjugate redox pairs

3A 3B 3C 3D 3E 3F 3G

3.1.13.1 Defining redox reactions

3.1.13.2 Identifying redox reactions using oxidation numbers

ESSENTIAL PRIOR KNOWLEDGE

- Electronegativity
- Metal reactivity

See questions 16–17.



Image: TZIDO SUN/Shutterstock.com

Why has the Statue of Liberty turned green over time?

Over the past 30 years, the once reddish-brown copper exterior of the Statue of Liberty has slowly been **oxidised**, giving us the iconic green statue we see today. This is a similar process to the rusting of iron, and it involves a series of **redox reactions**. In this lesson, we will learn about redox reactions and how **oxidation states** can help identify them.

KEY TERMS AND DEFINITIONS

Conjugate redox pair the electron donor (reactant/product) and its corresponding electron acceptor (product/reactant)

Half-equation reduction or oxidation equation of a complete redox reaction

Overall redox equation equation of a complete redox reaction combining reduction and oxidation half-equations

Oxidation chemical reaction in which a chemical species loses one or more electrons

Oxidation state number assigned to an atom that can be used to determine the movement of electrons in redox reactions

Oxidised describes a chemical species that has lost one or more electrons

Oxidising agent chemical species that oxidises another substance by accepting one or more electrons

Redox reaction chemical reaction involving the transfer of one or more electrons between chemical species

Reduced describes a chemical species that has gained one or more electrons

Reducing agent chemical species that reduces another substance by donating one or more electrons

Reduction chemical reaction in which a chemical species gains one or more electrons

Defining redox reactions 3.1.13.1

Redox reactions involve the balanced transfer of one or more electrons between chemical species.

What are redox reactions?

Redox reactions are a very common type of chemical reaction that involve the transfer of one or more electrons from one chemical species to another. As shown in figure 1, the term redox is a combination of two chemical processes: **reduction** and **oxidation**. As such, a redox reaction is the combination of a reduction and oxidation reaction, which occur simultaneously.



Figure 1 Formation of the term redox

STRATEGY

OIL RIG is a useful mnemonic for remembering the two parts to any redox reaction:

Oxidation Is Loss (of electrons)

Reduction Is Gain (of electrons)

Oxidation reactions generally involve a loss of one or more electrons from a chemical species. Conversely, reduction reactions generally involve a gain of one or more electrons. Consider the redox reaction occurring between species A and B shown in figure 2[1].

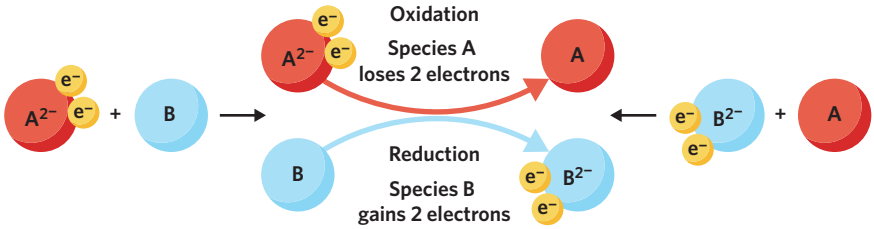


Figure 2 Model for redox reactions

The model illustrated in figure 2 shows that as species A loses 2 electrons, species B gains 2 electrons. As such, species A is said to undergo oxidation, and species B is said to undergo reduction.

During redox reactions, there will always be an **oxidising agent** and a **reducing agent**[2]. You may also see these referred to as an 'oxidant' and a 'reductant' respectively in VCAA exams prior to 2014.

A reducing agent causes another chemical species to be **reduced**. In other words, the reducing agent causes a species to gain one or more electrons. In contrast, an oxidising agent causes another species to be oxidised. This means that an oxidising agent causes another species to lose one or more electrons.

Redox equations can be expressed as two **half-equations** (figure 3), which are the equations of the oxidation and reduction reactions that make up the overall redox reaction. These are often referred to as half-reactions. **Overall redox equations** can also be written, which show the overall chemical reaction that occurs by combining two half-equations.

In a redox reaction, there will always be two **conjugate redox pairs**. One pair is made up of the oxidising agent (reactant) and the species formed when the oxidising agent is reduced (product). The other pair consists of the reducing agent (reactant) and the species formed when the reducing agent is oxidised (product). For example, during the redox reaction represented in figure 3, species A and A^+ will be one conjugate redox pair, and species B^+ and B will form the other pair.

If this reaction is reversed, species A^+ will be an oxidising agent and species B will be a reducing agent. For this reason, we can also refer to a conjugate redox pair as an oxidising agent and its corresponding reducing agent, and vice versa.

KEEN TO INVESTIGATE?

[1] **How are redox reactions used in rocket fuel?**
Search: What Makes a Rocket Soar?

USEFUL TIP

Oxidation can also be defined as the gain of oxygen or loss of hydrogen. Similarly, reduction can also be defined as the loss of oxygen or gain of hydrogen.

KEEN TO INVESTIGATE?

[2] **Why do copper statues turn green over time?**
Search: Why does copper turn green?

Oxidation (loss of an electron)

$A \rightarrow A^+ + e^-$

Reduction (gain of an electron)

$B^+ + e^- \rightarrow B$

Figure 3 Half-equations representing the oxidation of species A to form A^+ and the reduction of species B^+ to form B

USEFUL TIP

When looking at half equations, it is easy to differentiate between the oxidation and reduction reactions; in oxidation, the electron(s) is/are on the right hand side of the →, and in reduction the electron(s) is/are on the left hand side of the →.

MISCONCEPTION

'Oxidising agents are oxidised.'

Redox reactions involve the balanced transfer of one or more electrons between species, so oxidising agents must gain one or more electrons to balance the electrons they cause other species to lose (during oxidation). Therefore, oxidising agents are reduced, not oxidised.

PROGRESS QUESTIONS

Question 1

The reaction $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$ is an example of a(n)

A. oxidation half-equation.

B. reduction half-equation.

C. redox reaction.

D. species gaining electrons.

Question 2

Which of the following is a conjugate redox pair in the reaction represented by the following half-equations?

$Au^+(aq) + e^- \rightarrow Au(s)$

$Li(s) \rightarrow Li^+(aq) + e^-$

A. $Au^+(aq)$ and $Li(s)$

B. $Au^+(aq)$ and $Au(s)$

C. $Au(s)$ and $Li^+(aq)$

D. $Au(s)$ and $Li(s)$

Question 3

Which of the following statements is true about reducing agents?

A. They gain one or more electrons.

B. They lose one or more electrons.

C. They are reduced.

D. They cause another species to be oxidised.

Identifying redox reactions using oxidation numbers 3.1.13.2

Oxidation states are useful values that we can use to identify redox reactions.

How can we use oxidation numbers to identify redox reactions?

One technique that can be used to identify redox reactions is the use of oxidation states. Oxidation states indicate the charge that an atom may have as a result of the movement of one or more electrons during a redox reaction. A change in oxidation state of a chemical species indicates that one or more electrons have either been lost or gained, meaning that a redox reaction has occurred.

Oxidation states also allow us to identify which species has undergone oxidation and which species has undergone reduction. Table 1 shows some common rules for determining the oxidation state of different forms of elements.

Table 1 Common rules to determine the oxidation state of elements

Rule	Example
The oxidation state of a free element (an element by itself or bonded to itself) is always zero.	O_2, C, Cl_2
The oxidation state of a simple ion is equal to the charge of the ion.	Na^+, Cl^-, O^{2-}, Al^{3+}
The sum of oxidation states in a neutral compound is 0.	KCl, CO_2, $MgSO_4$
The sum of oxidation states in a polyatomic ion is equal to the charge of the ion.	SO_4^{2-}, NH_4^+, MnO_4^-
The normal oxidation state for hydrogen in a compound is +1 (except in metal hydrides, where it is −1).	HCl vs CaH_2
The normal oxidation state for oxygen in a compound is −2 (except in peroxides, where it is −1).	H_2O vs H_2O_2
The same element can be both oxidised and reduced in the equation (called disproportionation). In the decomposition of hydrogen peroxide, H_2O_2, oxygen is both oxidised and reduced. The oxidation states of oxygen are shown.	$\underset{-1}{H_2O_2} \rightarrow \underset{-2}{H_2O} + \underset{0}{\frac{1}{2}O_2}$

MISCONCEPTION

'−6 is a higher oxidation state than −2.'

The more negative an oxidation state, the lower the oxidation state of the given atom is. Similarly, the more positive an oxidation state, the higher it is.

Some of the trends in the oxidation states of individual elements of the periodic table are shown in figure 4.

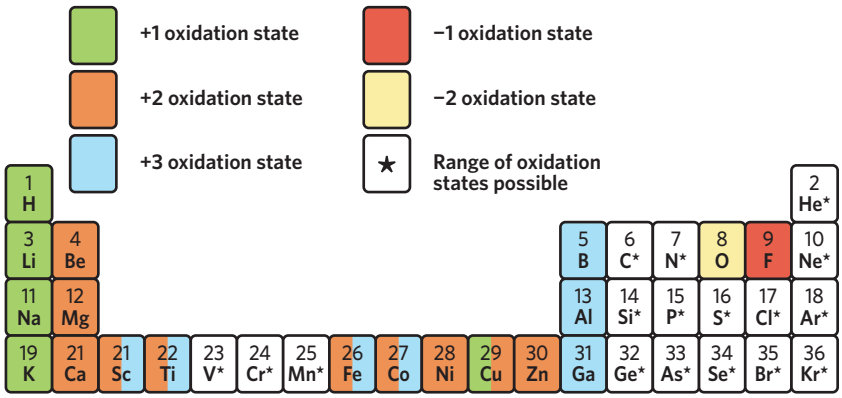


Figure 4 Periodic table showing the oxidation states of some common elements

Changes in oxidation states of atoms during redox reactions can help us identify whether an atom has been oxidised or reduced. An increase in oxidation number indicates that the atom has been oxidised, and therefore has lost electrons. It may be helpful to think of this loss of electrons (negative charge) as a gain in positive charge. Conversely, a decrease in oxidation numbers indicates that an atom has been reduced, and therefore has gained electrons. This gain in electrons (negative charge) can be thought of as a loss in positive charge.

WORKED EXAMPLE 1

Consider the following redox reaction.

$C(s) + O_2(g) \rightarrow CO_2(g)$

What is the reducing agent in this reaction? Justify your answer using oxidation states.

What information is presented in the question?

The balanced chemical reaction.

The chemical formulas for solid carbon, oxygen gas, and carbon dioxide gas.

What is the question asking us to do?

Determine the reducing agent in this reaction using oxidation states.

What strategies do we need in order to answer the question?

1. The oxidation state of free elements is 0.
2. The sum of the oxidation states of the atoms in a neutral compound (compound with an overall neutral charge) will be 0.
3. Oxygen atoms normally have an oxidation state of −2.
4. Reducing agents undergo oxidation.
5. When a species undergoes oxidation, its oxidation number increases.

Answer

All free elements have an oxidation state of 0. This means that C(s) and oxygen atoms in $O_2(g)$ all have an initial oxidation state of 0.

According to table 1, oxygen atoms in chemical compounds normally have an oxidation state of −2. We can use this information to calculate the oxidation number of carbon in CO_2. CO_2 has a net neutral charge, so the sum of the oxidation states of each element will equal zero.

Oxidation number of the carbon atom + two times the oxidation number of each oxygen atom = 0

Let x represent the oxidation number of the carbon atom. Therefore,

$x + 2 \times (-2) = 0$

$x - 4 = 0$

$x = +4$

Now we can see that the oxidation number of each oxygen atom decreases (0 to −2), whilst the oxidation number of the carbon atom increases (0 to +4). Since reducing agents are oxidised themselves, causing their oxidation number to increase, C(s) is the reducing agent in this reaction.

USEFUL TIP

When attempting to determine the oxidation state of an atom, it's important to note that the most electronegative atom in a compound or molecule will have a negative oxidation state. For example, in NO_2, the oxygen atoms will both have negative oxidation states, whereas in NH_3, the nitrogen will have a negative oxidation state.

MISCONCEPTION

'The average oxidation states of atoms in a compound are always whole numbers.'

Overall oxidation states in a compound do not always have to be whole numbers. The tetrathionate ion, $S_4O_6^{2-}$, has four sulfur ions with a combined oxidation state of +10, which means that the average is +2.5 per sulfur ion. This occurs because in tetrathionate, sulfur exists as 2 ions of +2 and 2 ions of +3.

PROGRESS QUESTIONS

Question 4

The oxidation state of phosphorus in the pyrophosphate ion $P_2O_7^{4-}$ is

A. +3.5
B. +5
C. +7
D. +10

VCAA 2012 Exam 1 Multiple choice Q19

Question 5

Which of the following unbalanced redox half-equations represents an oxidation reaction?

A. $Br_2(l) \rightarrow 2Br^-(aq)$
B. $Fe^{3+}(aq) \rightarrow Fe^{2+}(aq)$
C. $2H^+(aq) \rightarrow H_2(g)$
D. $Al(s) \rightarrow Al^{3+}(aq)$

Theory summary

- Redox reactions involve the transfer of one or more electrons from one species to another.
- Oxidation reactions (loss of electrons) and reduction reactions (gain of electrons) occur simultaneously.
- A reducing agent causes another species to be reduced by donating one or more electrons to that species. Therefore, it is itself oxidised.
- An oxidising agent causes another species to be oxidised by accepting one or more electrons from that species. Therefore, it is itself reduced.
- A conjugate redox pair consists of an oxidising agent (reactant/product) and it's corresponding reducing agent (product/reactant).
- An increase in oxidation number (loss of negative charge) of a species indicates that species has undergone oxidation.
- A decrease in oxidation number (gain in negative charge) of a species indicates that species has undergone reduction.

3A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 6–8.

Iron rusts in a reaction with oxygen in moist air to form iron oxide according to the simplified equation.

$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s)$



Image: Burben/Shutterstock.com

Question 6 (1 MARK)

Which of the following is true when a species is oxidised?

A. The species gains electrons.

B. The species causes another species to lose electrons.

C. The oxidation number of the species increases.

D. The oxidation number of the species decreases.

Question 7 (1 MARK)

What are the initial and final oxidation states of iron (Fe) according to the above redox equation?

A. 0 and +3

B. 0 and +6

C. +1 and +3

D. +1 and +6

Question 8 (2 MARKS)

Which species is the reducing agent in this reaction? Justify your answer using oxidation states.

Exam-style

Question 9 (1 MARK)

In which one of the following compounds is sulfur in its lowest oxidation state?

A. SO_3

B. HSO_4^-

C. SO_2

D. Al_2S_3

VCAA 2015 exam Multiple choice Q6

Question 10 (1 MARK)

Which of the following represents a balanced reduction half-reaction?

A. $VO_2^+ + H^+ + 2e^- \rightarrow VO^{2+} + H_2O$

B. $VO_2^+ + H_2 \rightarrow VO^{2+} + H_2O + e^-$

C. $VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O$

D. $VO_2^+ + 4H^+ + 3e^- \rightarrow VO^{2+} + 2H_2O$

VCAA 2010 Exam 2 Multiple choice Q16

Question 11 (2 MARKS)

Zinc chloride could theoretically be produced in a reaction between zinc sulfate ($ZnSO_4$) and hydrochloric acid (HCl) according to the following equation:

$ZnSO_4(aq) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2SO_4(aq)$

Is this reaction an example of a redox reaction? Explain.

Question 12 (3 MARKS)

Sulfuric acid is widely used to produce fertilisers. In particular, it reacts with ammonia to produce ammonium sulfate as shown in the reaction provided.

$2NH_3(g) + H_2SO_4(aq) \rightarrow (NH_4)_2SO_4(aq)$

a. Determine the oxidation number for sulfur in H_2SO_4. 1 MARK

b. Which species in the reaction have not experienced a change in oxidation number? 1 MARK

c. Is the above reaction a redox reaction? 1 MARK

Question 13 (4 MARKS)

Consider the following redox reaction:

$Cl_2(g) + H_2(g) \rightarrow 2HCl(aq)$

a. Which species loses electrons in this reaction? 1 MARK

b. What is the conjugate redox pair that includes this species? 1 MARK

c. What is the oxidising agent in this reaction? 1 MARK

d. What is the oxidation state of the oxidising agent's conjugate? 1 MARK

Question 14 (3 MARKS)

During an experiment, solid zinc metal was burned in a crucible, resulting in the formation of a white substance. Based on the chemical equation provided:

$2Zn(s) + O_2(g) \rightarrow 2ZnO(s)$

a. Identify the species undergoing oxidation. Use oxidation numbers to justify your answer. 2 MARKS

b. What is the oxidising agent in this reaction? 1 MARK

Key science skills

Question 15 🌶🌶🌶 (10 MARKS)

When a coil of solid copper wire reacts with silver nitrate solution under standard conditions, silver crystals form on its surface. The solution also begins to turn blue as copper ions are released into the solution.

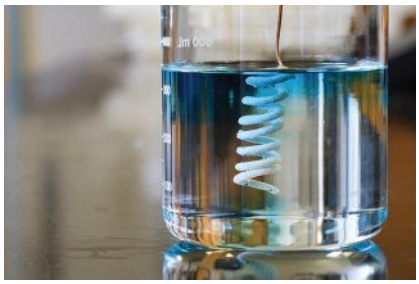


Image: ggw/Shutterstock.com

This is a type of redox reaction, where solid copper is oxidised to form copper cations, and silver cations are reduced to form solid silver according to the following chemical equation.

$Cu(s) + 2Ag^{+}(aq) \rightarrow Cu^{2+}(aq) + 2Ag(s)$

Chemistry students Kiran and Noor want to investigate the changes in mass of both the wire and the system during this reaction over the course of ten minutes. They do this by recording the mass of the copper wire using an electronic balance before and after the reaction occurs, and they also record the mass of the beaker containing the wire and the salt solution.

a. Will the wire gain or lose mass? Justify your answer. Calculations are not required. 2 MARKS

b. How much will the mass of the wire change for every mole of solid copper reacted? 3 MARKS

c. Kiran predicts that the mass of the system will change because the mass of the wire has changed and the mass of the solution has stayed the same. Noor disagrees, and suggests that according to the law of conservation of mass, the mass of the beaker's contents must stay the same.
Who is correct? Justify your answer. 3 MARKS

d. Noor and Kiran repeat the experiment the next day using an identical copper wire. However, they find that the change in mass of the wire over the course of ten minutes is significantly larger than the results from the previous day. What could have caused this to occur, and what effect does this have on the validity of the experiment? 2 MARKS

FROM LESSONS 12B & 12D

Questions from multiple lessons

Question 16 🌶🌶 (3 MARKS)

Propane (C_3H_8) is a hydrocarbon that is commonly used as a fuel source.

a. Write the balanced complete combustion reaction of propane. 1 MARKS

b. Which chemical species is being oxidised and which chemical species is being reduced?
Refer to oxidation states in your answer. 2 MARKS

FROM LESSON 1D

Question 17 🌶🌶 (4 MARKS)

Photosynthesis is the chemical process that converts light energy into chemical energy in plants. Consider the following chemical equation for photosynthesis.

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

a. Is photosynthesis a redox reaction? Justify your answer using oxidation states. 2 MARKS

b. Is this reaction endothermic or exothermic? 1 MARK

c. Sketch the shape of an energy profile diagram to represent this reaction. You are not required to create a scale on either axis. 1 MARK

FROM LESSONS 1C & 1D

3B Writing redox equations

STUDY DESIGN DOT POINT

- the writing of balanced half-equations (including states) for oxidation and reduction reactions, and the overall redox cell reaction in both acidic and basic conditions

3A **3B** 3C 3D 3E 3F 3G

- 3.1.14.1 Balancing half-cell redox reactions
- 3.1.14.2 Balancing overall redox reactions

ESSENTIAL PRIOR KNOWLEDGE

- Acid-base reactions

3A Redox reactions

See questions 18–19.



Image: Ihor Matsiievskyi/Shutterstock.com

How can redox reactions cause a change in colour?

Some chemical species that change colour when they are either oxidised or reduced can be used instead of indicators in redox titrations, which will be explored in lesson 9D. In this lesson, we will learn how to balance redox half-equations and overall redox equations.

KEY TERMS AND DEFINITIONS

Acidic environment solution with a greater concentration of hydrogen ions (H^+) than hydroxide ions (OH^-)

Basic environment solution with a greater concentration of hydroxide ions (OH^-) than hydrogen ions (H^+)

Balancing half-cell redox reactions 3.1.14.1

Half-equations must be correctly balanced to accurately represent redox reactions. KOHES is a helpful mnemonic we can use to balance redox half-equations.

How can we use KOHES to balance redox half-equations?

In lesson 3A we investigated the processes of oxidation (the loss of one or more electrons) and reduction (the gain of one or more electrons). These two processes occur simultaneously, with oxidation reactions paired with reduction reactions to allow the transfer of electrons between chemical species. A redox half-equation is a chemical equation that describes either the individual oxidation or reduction reaction that is occurring within the overall redox reaction.

Consider the following oxidation reaction, characterised by an increase in oxidation number.[1] Although there is one iron atom on either side of the equation, the charges are unbalanced.

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq)$

KEEN TO INVESTIGATE?

1 **Why does a change in oxidation state cause colour changes?**
Search YouTube: oxidation states of vanadium

In order to balance charges in a chemical equation, electrons are added to the more positive side of the equation. In this case, the reactants have an overall charge of +2 and the products have an overall charge of +3. Therefore, one electron can be added to the products so that both sides of the equation are balanced, as they now each have an overall charge of +2.

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$

MISCONCEPTION

'The charge of each side of a balanced equation must be 0.'
The charges on each side of a balanced equation must be equal. This charge may be 0, but this is not always the case.

However, this is only a simple case of balancing a half-reaction, as only the charge needed to be balanced. In more complex cases, the mnemonic KOHES describes the steps that must be followed in order to correctly balance a half-equation:

Key elements need to be balanced.

Oxygen atoms need to be balanced by adding H_2O.

Hydrogen atoms need to be balanced by adding H^+ in **acidic environments**. (In **basic environments**, OH^- ions must be added to both sides of the equation to neutralise all H^+ ions.)

Electrons need to be added to balance charge.

States need to be included.

Figure 1 shows how KOHES can be applied to the reduction half-equation for the dichromate ion in an acidic environment.

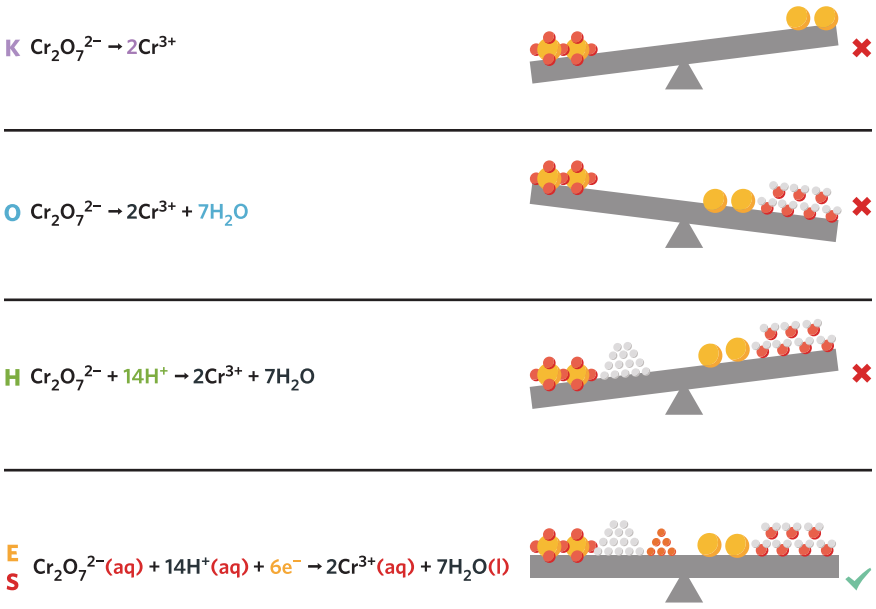


Figure 1 Balancing the half-equation for the reduction of $Cr_2O_7^{2-}(aq)$ to $2Cr^{3+}(aq)$

When a redox reaction[2] occurs under acidic conditions, we can assume that there are free H^+ ions available to balance hydrogen atoms in a half-equation. However, these will not be present in basic environments. This means that each time an H^+ ion is added to a half-equation in a basic environment, an OH^- (hydroxide) anion must be added to each side of the equation.

From acid-base chemistry, we know that:

$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$

Therefore, OH^- anions will be present in the half-equation instead of H^+ cations, indicating that the reaction takes place under basic conditions.

USEFUL TIP

Electrons are not molecules or atoms, so they do not need to be written with a state (solid, liquid, gas or aqueous) in half-equations.

KEEN TO INVESTIGATE?

[2] **What makes a stain remover more environmentally friendly?**
Search : A greener bleach

WORKED EXAMPLE 1

The permanganate ion MnO_4^- is a very common oxidising agent and can be reduced to MnO_2.
Balance the half-equation for the reduction of $MnO_4^-(aq)$ to form $MnO_2(s)$ in a basic environment.

What information is presented in the question?

$MnO_4^-(aq)$ is reduced to form $MnO_2(s)$.

There is a source of $OH^-(aq)$, as the reaction takes place under basic conditions.

What is the question asking us to do?

Write the balanced half-equation for the reduction of $MnO_4^-(aq)$ to $MnO_2(s)$.

What strategies do we need in order to answer the question?

Using KOHES:

1. Balance key elements.
2. Balance oxygen atoms using H_2O.
3. Balance hydrogen atoms using H^+.
4. In basic conditions, add an OH^- to each side of the equation for every H^+ ion. In basic environments, OH^- ions must be added to both sides of the equation to neutralise all H^+ ions.
5. Balance charge using electrons.
6. Add states.

Answer

The key element, manganese (Mn) is already balanced.

$MnO_4^- \rightarrow MnO_2$

Two H_2O molecules are added to the products side to balance oxygen atoms.

$MnO_4^- \rightarrow MnO_2 + 2H_2O$

Four H^+ atoms are added to the reactants side to balance hydrogen atoms.

$MnO_4^- + 4H^+ \rightarrow MnO_2 + 2H_2O$

As this reaction takes place under basic conditions, four OH^- ions are added to each side of the equation to neutralise the four H^+ ions.

$MnO_4^- + 4H^+ + 4OH^- \rightarrow MnO_2 + 2H_2O + 4OH^-$

The four H^+ and OH^- ions on the reactant side undergo a neutralisation reaction to form four H_2O molecules.

$MnO_4^- + 4H_2O \rightarrow MnO_2 + 2H_2O + 4OH^-$

There are now H_2O molecules on each side of the equation. These can be cancelled as follows.

$MnO_4^- + 2H_2O \rightarrow MnO_2 + 4OH^-$

The reactants have an overall charge of -1 and the products have an overall charge of -4. Three electrons can be added to the reactants to balance these charges, so that each side of the equation has a charge of -4.

$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4OH^-$

Finally, states must be added. Therefore, the final balanced half-equation is:

$MnO_4^-(aq) + 2H_2O(l) + 3e^- \rightarrow MnO_2(s) + 4OH^-(aq)$

USEFUL TIP

If there is a certain species on both the reactants side (including electrons) and the products side of a chemical equation, they can be cancelled out from both sides until one side has none of that species left. For example,

$MnO_4^- + 4H_2O \rightarrow MnO_2 + 2H_2O + 4OH^-$

$MnO_4^- + 2\cancel{4}H_2O \rightarrow MnO_2 + \cancel{2H_2O} + 4OH^-$

$MnO_4^- + 2H_2O \rightarrow MnO_2 + 4OH^-$

PROGRESS QUESTIONS

Question 1

Consider the following unbalanced half-equation showing the oxidation of tin ions.

$Sn^{2+}(aq) \rightarrow Sn^{4+}(aq)$

What must be added in order for this half-equation to be balanced?

A. 2 electrons to the products

B. 2 electrons to the reactants

C. 2 electrons to the products and 4 electrons to the reactants

D. 2 electrons to the reactants and 4 electrons to the products

Continues →

Question 2

The manganese ion, $MnO_4^-(aq)$, is a strong oxidising agent. What is the balanced reduction half-equation when it is reduced to $Mn^{2+}(aq)$ in basic conditions?

A. $MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 4H_2O(l)$

B. $MnO_4^-(aq) + 4H_2O(l) + 5e^- \rightarrow Mn^{2+}(aq) + 8OH^-(aq)$

C. $Mn^{2+}(aq) + 8OH^-(aq) \rightarrow MnO_4^-(aq) + 4H_2O(l) + 5e^-$

D. $Mn^{2+}(aq) + 4H_2O(l) \rightarrow MnO_4^-(aq) + 8H^+(aq) + 5e^-$

Question 3

Hydrogen sulfite, HSO_3^-, is oxidised to form the polyatomic sulfate ion, SO_4^{2-}, in an acidic aqueous solution. What is the balanced oxidation half-equation for this reaction?

A. $HSO_3^-(aq) + 2H_2O(l) \rightarrow SO_4^{2-}(aq) + 4H^+(aq) + e^-$

B. $SO_4^{2-}(aq) + 3H^+(aq) + 2e^- \rightarrow HSO_3^-(aq) + H_2O(l)$

C. $HSO_3^-(aq) + H_2O(l) \rightarrow SO_4^{2-}(aq) + 3H^+(aq) + 2e^-$

D. $SO_4^{2-}(aq) + 2H^+(aq) + e^- \rightarrow HSO_3^-(aq) + H_2O(l)$

Balancing overall redox reactions 3.1.14.2

Overall equations are formed by combining oxidation and reduction half-equations.

How can we write overall redox equations?

Since oxidation and reduction half-equations are always coupled together, an overall redox equation that combines these two half-equations can provide an overview of the reactants and products of a redox reaction.

Consider the following oxidation and reduction half-equations, where potassium is oxidised and chlorine is reduced.

Oxidation: $K(s) \rightarrow K^+(aq) + e^-$

Reduction: $Cl_2(g) + 2e^- \rightarrow 2Cl^-(aq)$

Since redox reactions involve the balanced transfer of electrons, the equation for the oxidation of K(s) can be multiplied by two so that there is the same number of electrons transferred in each half-equation.

Oxidation: $2 \times (K(s) \rightarrow K^+(aq) + e^-)$

$2K(s) \rightarrow 2K^+(aq) + 2e^-$

Now that there is an equal number of electrons on each side, the two half-equations can be added together, producing the overall equation.

Overall: $2K(s) + Cl_2(g) + \cancel{2e^-} \rightarrow 2K^+(aq) + 2Cl^-(aq) + \cancel{2e^-}$

Since there are two electrons present on both sides of the equation, they can be removed, leaving the final overall balanced redox equation, where the charge on both sides of the equation is 0.

Overall: $2K(s) + Cl_2(g) \rightarrow 2K^+(aq) + 2Cl^-(aq)$

The above example shows the formation of the overall equation from two very simple half-equations. An example of a more complex unbalanced redox reaction between the dichromate ion and nitrous acid is shown below.

$Cr_2O_7^{2-}(aq) + HNO_2(aq) \rightarrow Cr^{3+}(aq) + NO_3^-(aq)$

This equation would be very difficult to balance without using half-reactions. To determine a balanced overall equation, we find its respective reduction and oxidation half-equations and then add them together. This process is shown in the following worked example.

MISCONCEPTION

'Electrons will be present in an overall redox equation.'

No additional electrons are consumed or produced during a redox reaction. Therefore, overall redox equations will not have electrons present on either the reactants' or products' side of the equation. This gives you a useful way to check that you've combined the half-equations correctly; if there are uncancelled electrons in your final answer, a mistake has been made!

WORKED EXAMPLE 2

Balance the following redox reaction under acidic conditions.

$Cr_2O_7^{2-}(aq) + HNO_2(aq) \rightarrow Cr^{3+}(aq) + NO_3^-(aq)$

What information is presented in the question?

The unbalanced chemical equation under acidic conditions.

What is the question asking us to do?

Write out the balanced overall equation.

What strategies do we need in order to answer the question?

Using KOHES:

1. Use oxidation states to identify the conjugate redox pairs, which will be reactants and products in each half-equation.
2. Balance each half-equation using KOHES.
3. Make each half-equation have the same number of transferred electrons by multiplying one or both of the equations by a whole number.
4. Add the equations together to determine the overall redox equation.

Answer

The oxidation number of Cr decreases from +6 in $Cr_2O_7^{2-}$ to +3 in Cr^{3+}, so $Cr_2O_7^{2-}$ and Cr^{3+} form one conjugate redox pair.

The oxidation number of N increases from +3 in HNO_2 to +5 in NO_3^-, so HNO_2 and NO_3^- form the other conjugate redox pair.

Using KOHES under acidic conditions,

$Cr_2O_7^{2-} \rightarrow Cr^{3+}$

Is balanced to

$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \rightarrow 2Cr^{3+}(aq) + 7H_2O(l)$

Again using KOHES under acidic conditions,

$HNO_2 \rightarrow NO_3^-$

Is balanced to

$HNO_2(aq) + H_2O(l) \rightarrow NO_3^-(aq) + 3H^+(aq) + 2e^-$

To be able to add these together to form the overall equation, the second equation must be multiplied by three so that each equation contains six electrons.

$3 \times (HNO_2(aq) + H_2O(l) \rightarrow NO_3^-(aq) + 3H^+(aq) + 2e^-)$

$3HNO_2(aq) + 3H_2O(l) \rightarrow 3NO_3^-(aq) + 9H^+(aq) + 6e^-$

These half-equations can now be added together to form an overall equation.

$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- + 3HNO_2(aq) + 3H_2O(l) \rightarrow 2Cr^{3+}(aq) + 7H_2O(l) + 3NO_3^-(aq) + 9H^+(aq) + 6e^-$

After cancelling species that appear on both sides of the equation, we are left with the following final balanced overall redox equation where the charge on each side of the equation is +3.

$Cr_2O_7^{2-}(aq) + 5H^+(aq) + 3HNO_2(aq) \rightarrow 2Cr^{3+}(aq) + 3NO_3^-(aq) + 4H_2O(l)$

PROGRESS QUESTIONS

Question 4

A particular redox reaction is characterised by the following oxidation and reduction half-equations.

Oxidation: $Na(s) \rightarrow Na^+(aq) + e^-$

Reduction: $Sn^{2+}(aq) + 2e^- \rightarrow Sn(s)$

Which of the following represents the balanced overall redox reaction?

A. $Na(s) + Sn^{2+}(aq) \rightarrow Na^+(aq) + Sn(s)$

B. $Na(s) + e^- + Sn^{2+}(aq) \rightarrow Na^+(aq) + Sn(s)$

C. $2Na(s) + Sn^{2+}(aq) \rightarrow 2Na^+(aq) + Sn(s)$

D. $Na(s) + 2Sn^{2+}(aq) \rightarrow Na^+(aq) + 2Sn(s)$

Question 5

Which of the following descriptions aligns with the chemical reaction shown?

$Cr_2O_7^{2-}(aq) + 6e^- + 14H^+(aq) \rightarrow 2Cr^{3+}(aq) + 7H_2O(l)$

A. Overall redox equation in acidic conditions

B. Overall redox equation in basic conditions

C. Redox half-equation in acidic conditions

D. Redox half-equation in basic conditions

Theory summary

- Half-equations can be balanced using KOHES.
  - **K**ey elements need to be balanced.
  - **O**xygen atoms need to be balanced by adding H_2O.
  - **H**ydrogen atoms need to be balanced by adding H^+ in acidic environments. In basic environments, OH^- ions must be added to both sides of the equation to neutralise all H^+ ions.
  - **E**lectrons need to be added to balance charge.
  - **S**tates need to be included.
- Under basic conditions, an OH^- ion must be added to both sides of a redox half-equation for every H^+ ion present.
  - H^+ ions can react with OH^- ions to form H_2O.
- A complete redox reaction can be determined by adding the reduction and oxidation half-equations together if they both contain the same number of electrons.
  - If two half-equations contain a different number of electrons, one or both of the half-equations can be multiplied by a whole number so that they contain the same number of transferred electrons.

3B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed

Use the following information to answer questions 6–8.

$KMnO_4$ is often used as a titrant (flows through burette) in redox titrations. This is because MnO_4^- ions start as a deep purple colour and are reduced to form Mn^{2+} ions, which are colourless. This means that when all of the analyte (other species $KMnO_4$ is titrated against in a conical flask) reaches the equivalence point and ceases to reduce MnO_4^- ions, the mixture will undergo a permanent colour change to become purple.

Consider the redox titration between $MnO_4^-(aq)$ and $Fe^{2+}(aq)$, which occurs in an acidic environment.

Question 6 🌶 (1 MARK)

The main difference when using KOHES to balance redox reactions occurring in acidic and basic conditions is that

A. the overall redox equation will not contain H^+ ions in acidic conditions.

B. the overall redox equation will not contain OH^- ions in basic conditions.

C. OH^- ions must be added to both sides of the equation in acidic conditions for every H^+ ion present.

D. OH^- ions must be added to both sides of the equation in basic conditions for every H^+ ion present.

Question 7 🌶 (1 MARK)

Using KOHES, how can charges be balanced once all species in the half-equation are balanced?

A. Hydrogen ions can be added.

B. Electrons can be added.

C. Hydrogen ions can be removed.

D. Electrons can be removed.

Question 8 🌶🌶 (3 MARKS)

Write out each half-equation as well as the resulting overall equation for the redox reaction that occurs during this titration. In this reaction, Fe^{2+} ions are oxidised to Fe^{3+}.

Exam-style

Question 9 (1 MARK)

An aqueous solution of ethanol, CH_3CH_2OH, left exposed to the air, will undergo a redox reaction with oxygen, O_2, to form ethanoic acid, CH_3COOH.

The half-equation for the oxidation reaction is

A. $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$

B. $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$

C. $CH_3CH_2OH(aq) + H_2O(l) \rightarrow CH_3COOH(aq) + 4H^+(aq) + 4e^-$

D. $CH_3CH_2OH(aq) + \frac{1}{2}O_2(g) \rightarrow CH_3COOH(aq) + 2H^+(aq) + 2e^-$

VCAA (NHT) 2018 exam Multiple choice Q11

Question 10 (2 MARKS)

The reaction between hydrogen peroxide and ammonium ions is represented by the following equation.

$3H_2O_2(aq) + 2NH_4^+(aq) \rightarrow N_2(g) + 2H^+(aq) + 6H_2O(l)$

a. Write down the half-equation for the reduction reaction. 1 MARK

b. Write down the half-equation for the oxidation reaction. 1 MARK

Adapted from VCAA 2015 exam Multiple choice Q24

Question 11 (3 MARKS)

A student decided to set up a redox reaction involving the oxidising agent, $Cr_2O_7^{2-}(aq)$, in order to oxidise methanol, $CH_3OH(l)$. The following half-equations represent the reaction, but are incomplete and unbalanced.

$Cr_2O_7^{2-}(aq) \rightarrow Cr^{3+}(aq)$

$CH_3OH(l) \rightarrow HCOOH(l)$

a. Write out the reduction and oxidation half-equations under acidic conditions, denoting which is the reduction and which is the oxidation half-equation. 2 MARKS

b. Write out the overall equation. 1 MARK

Question 12 (3 MARKS)

Silver oxide, Ag_2O, is commonly used in household batteries, where it undergoes a redox reaction with zinc. The incomplete, unbalanced redox reaction is provided, which occurs under basic conditions. States are not required.

$Ag_2O + Zn \rightarrow Ag + Zn(OH)_2$

a. Write the balanced oxidation half-equation for the reaction. 1 MARK

b. Write the balanced reduction half-equation for the reaction. 1 MARK

c. Write the full balanced redox equation for this reaction. 1 MARK

Question 13 (2 MARKS)

Redox reactions occur in the human body. Nicotinamide adenine dinucleotide (NAD) is a vital enzyme for energy production in the human body. It exists in two forms: an oxidised form, NAD^+, and a reduced form, NADH.

NAD is involved in the conversion of ethanol, CH_3CH_2OH, to ethanal, CH_3CHO, in the human body.

The overall equation for this redox reaction is

$CH_3CH_2OH + NAD^+ \rightarrow CH_3CHO + NADH + H^+$

a. Write the oxidation half-equation for this redox reaction. States are not required. 1 MARK

b. Write the reduction half-equation for this redox reaction. States are not required. 1 MARK

VCAA 2018 exam Short answer Q6ai

Question 14 (1 MARK)

The following equation is an example of an unbalanced overall redox reaction.

$MnO_4^-(aq) + H^+(aq) + Li(s) \rightarrow Mn^{2+}(aq) + H_2O(l) + Li^+(aq)$

When it is correctly balanced, what is the coefficient of Li(s)?

A. 3 **B.** 4 **C.** 5 **D.** 6

Key science skills

Question 15 (11 MARKS)

Potassium is a highly reactive metal that reacts explosively when exposed to water, and is oxidised easily by oxygen in the air. This means that certain precautions must be taken to ensure that it is stored and reacted safely and as intended.

Chemistry student Jade observed a demonstration of this explosive reaction between potassium and water. They observed a bright purple flame that ignited a few seconds after the metal was put in a glass trough of water, but fizzled out shortly after. They know that potassium hydroxide (KOH) and hydrogen gas (H_2) are formed during this reaction.



a. Given the above information, suggest how potassium metal should be stored before use. Provide a reason for your answer. 2 MARKS

b. What are three potential risks in this demonstration that Jade's teacher should consider? For each answer, provide a precaution that should be taken to minimise this risk. 6 MARKS

c. Following the demonstration, Jade's class is asked to balance the oxidation half-equation for this redox reaction. They arrive at the following incorrect answer.

$2K(s) + O_2(g) + 2H_2O(l) + 2e^- \rightarrow 2KOH(aq) + 2OH^-(aq)$

i. Suggest why this answer is incorrect. Give two possible reasons. 2 MARKS

ii. Write out the correct oxidation half-equation. 1 MARK

FROM LESSONS 12B & 12D

Questions from multiple lessons

Question 16 (5 MARKS)

Sulfur dioxide gas, $SO_2(g)$, can be produced in a reaction between sulfuric acid, $H_2SO_4(aq)$, and nickel metal, Ni(s). After the reaction occurs, Ni^{2+} ions are found in the solution.

a. Write balanced oxidation and reduction half-equations for this process. 2 MARKS

b. Write a balanced overall reaction. 1 MARK

c. Sulfur dioxide can also be produced in a reaction between calcium sulfate, silicon dioxide (from sand), and pure carbon, when they are heated together in a furnace according to the following equation.

$2CaSO_4(s) + 2SiO_2(s) + C(s) \rightarrow 2CaSiO_3(s) + 2SO_2(g) + CO_2(g)$

Is this reaction an example of a redox reaction? Explain. 2 MARKS

FROM LESSON 3A

Question 17 🌶🌶🌶 (6 MARKS)

Cellular respiration is an important process that supplies energy for the body, and is a type of redox reaction. In this reaction, glucose, $C_6H_{12}O_6$, is oxidised by oxygen, O_2. The overall equation for this reaction is shown.

$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$

a. Write balanced oxidation and reduction half-equations for this reaction in an acidic environment. 2 MARKS

b. Photosynthesis is an essential process for the survival of plants, and is the reverse reaction of cellular respiration. It can be represented by the following equation:

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

It is known that photosynthesis is a non-spontaneous redox reaction, whereas cellular respiration is a spontaneous redox reaction.

i. Explain why this may be the case, with reference to thermochemistry. 3 MARKS

ii. Where do plants obtain the energy input required for this reaction to occur, which is subsequently converted to chemical energy? 1 MARK

FROM LESSONS 1C & 1D

3C Primary galvanic cells

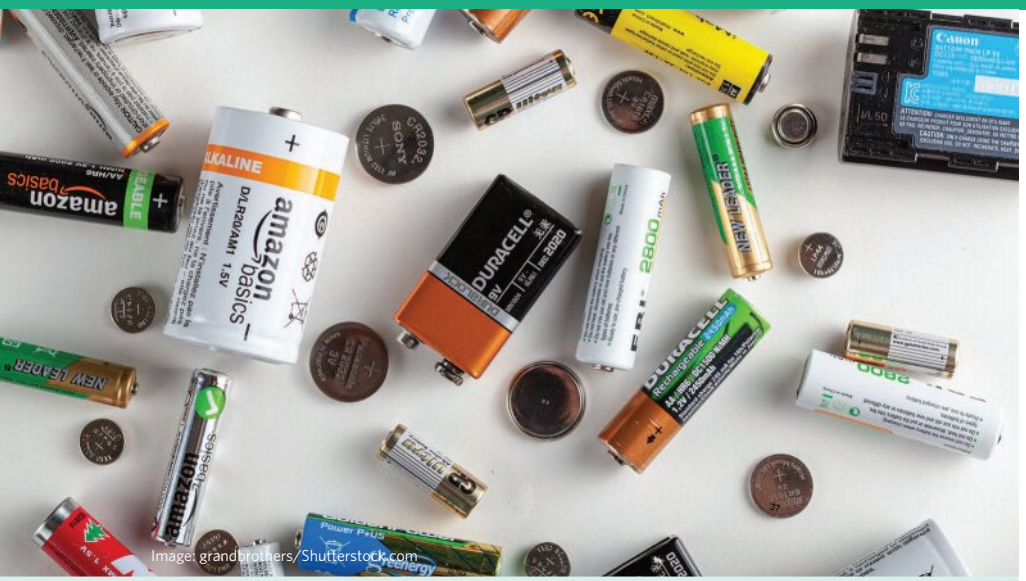


Image: grandbrothers/Shutterstock.com

How do different types of batteries work?

All household batteries are types of **electrochemical cells** that produce energy through redox reactions. These are either **primary cells** (non-rechargeable) or secondary cells (rechargeable), which will be covered in lesson 6C.
In this lesson, we will learn how primary **galvanic cells** convert chemical energy into electrical energy through redox reactions.

KEY TERMS AND DEFINITIONS

Anode electrode where oxidation (loss of electrons) occurs
Cathode electrode where reduction (gain of electrons) occurs
Current a flow of charged particles (ions or electrons)
Electrochemical cell cell involving conversions between electrical and chemical energy
Electrochemical series ranking of chemical species in order of their reducing and oxidising strength
Electrode electrically conductive medium
Electrolyte solution, liquid, or gel containing ions
External circuit flow of electrons through an external wire
Feasible reaction a reaction that could occur but will not necessarily spontaneously react or be observable
Galvanic cell electrochemical cell in which chemical energy from spontaneous redox reactions is converted into electrical energy
Half-cell half of a galvanic cell where either oxidation or reduction reactions occur separated from the other half-cell
Internal circuit flow of ions through a salt bridge
Primary cell cell that cannot be recharged
Salt bridge connection that allows the flow of ions between two half-cells to complete the circuit

STUDY DESIGN DOT POINTS

- the common design features and general operating principles of non-rechargeable (primary) galvanic cells converting chemical energy into electrical energy, including electrode polarities and the role of the electrodes (inert and reactive) and electrolyte solutions
- the use and limitations of the electrochemical series in designing galvanic cells and as a tool for predicting the products of redox reactions, for deducing overall equations from redox half-equations and for determining maximum cell voltage under standard conditions

3A 3B **3C** 3D 3E 3F 3G

- 3.1.15.1 Design of galvanic cells
- 3.1.15.2 Function of galvanic cells
- 3.1.15.3 Identifying half-cell reactions in galvanic cells
- 3.1.16.1 Limitations of the electrochemical series

ESSENTIAL PRIOR KNOWLEDGE

- Electrical circuits
- Carbon allotropes

See questions 20–21.

Design of galvanic cells 3.1.15.1

A galvanic cell is an electrochemical cell that consists of two **half-cells** that are connected by a wire and a salt bridge to create a complete electric circuit.

What are the key features of galvanic cells?

A galvanic cell is a type of electrochemical cell that converts chemical energy into electrical energy through spontaneous redox reactions. This lesson will discuss the design and function of primary galvanic cells. Primary cells are non-rechargeable, meaning the products of the reactions that occur in primary galvanic cells are disposed of after the reaction runs its course.

Spontaneous redox reactions are always exothermic, as less stable (higher energy) reactants are converted into more stable (lower energy) products. When spontaneous oxidation and reduction reactions occur in the same container, this energy is released as heat (thermal energy). However, when spontaneous reduction and oxidation reactions occur in separate containers, a complete circuit can be constructed so that the electrons transferred during these reactions flow through a wire as ions flow through a **salt bridge**. This allows chemical energy to be converted into and utilised as electrical energy.

Figure 1 shows the construction of a standard galvanic cell. A galvanic cell consists of two separate half-cells connected by a salt bridge, containing an unreactive ionic salt solution.[1] Each half cell contains an electrode made out of a conductive material, often a metal or pure carbon rod. The positive electrode, known as the **cathode**, will be located in the half-cell where reduction takes place. Conversely, the negative electrode, known as the **anode**, will be found in the half-cell where oxidation takes place. As shown in figure 1, each electrode is partially submerged in the solutions (**electrolyte**) of its half-cell and are connected by a metal wire.

USEFUL TIP

Electrodes are not always directly involved in galvanic cell reactions. These electrodes will typically either be inert (unreactive) metals (such as platinum, Pt) or inert conductive materials (such as graphite, C).

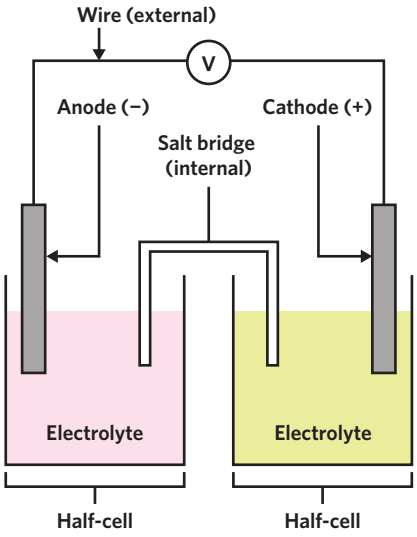


Figure 1 Simple structure of a galvanic cell

KEEN TO INVESTIGATE?

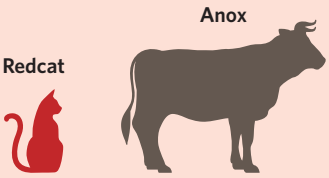
[1] **Why do we need salt to survive?** Search: Electrolytes: types, purpose and normal levels

USEFUL TIP

An 'electrolyte' is a solution, liquid or a gel that contains ions. This means that any ionic solutions in each half-cell can also be referred to as electrolytes.

STRATEGY

A useful mnemonic for remembering the sites of oxidation and reduction in a galvanic cell is 'RedCat AnOx':



RedCat – **Red**uction occurs at the **cat**hode.

AnOx – **An**ode is the site of **ox**idation.

PROGRESS QUESTIONS

Question 1

Which of the following statements is correct about the set-up of a galvanic cell?

A. The solutions in two half-cells are connected by a wire.

B. The two electrodes are connected by a salt bridge.

C. The solutions in two half-cells are connected by a salt bridge.

D. The anode and cathode are fully submerged in the electrolyte.

Function of galvanic cells 3.1.15.2

Galvanic cells convert chemical energy into electrical energy from the reduction and oxidation reactions occurring in each half-cell.

How can we produce electrical energy from galvanic cells?

Galvanic cells convert chemical energy into electrical energy.[2] **Current** is produced as electrons released during oxidation reactions flow from the anode to the cathode, where they are gained by a chemical species in the reduction reaction. This forms the cell's **external circuit.**

MISCONCEPTION

'Galvanic cells are 100% efficient.'

Galvanic cells are not completely efficient; some chemical energy is 'lost' as heat, in addition to being converted into electrical energy.

KEEN TO INVESTIGATE?

[2] **How do household batteries convert chemical energy into electrical energy?**
Search: Commercial galvanic cells chemistry

The salt bridge connects the electrolytes of two separated half-cells, and completes the cell's electrical circuit by allowing the flow of ions between half-cells without the electrolytes mixing. The ionic salt solution in the salt bridge contains positively and negatively charged ions that are able to flow into each half-cell. As electrons are removed at the anode, this lost negative charge is replenished as anions from the salt bridge migrate towards the anode (oxidation half-cell). Similarly, as electrons are gained at the cathode, this increase in negative charge is offset as cations from the salt bridge flow towards the cathode (reduction half-cell). This flow of ions (charge) through the salt bridge is referred to as the **internal circuit**.

In order for a salt solution to be suitable for use in a salt bridge, it must be very soluble in water, unreactive and not form an insoluble compound (precipitate) with any species in either half-cell. This means that these ions will not undergo any chemical reactions themselves, and will instead be spectator ions during galvanic cell reactions.

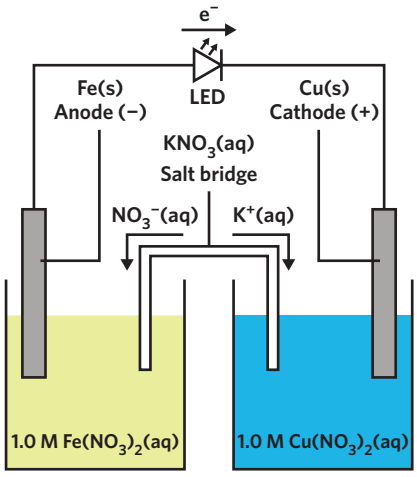


Figure 2 Illustration of a galvanic cell's function

MISCONCEPTION

'Electrons flow through the salt bridge.'

The **E**xternal circuit (wires) allows **E**lectrons to flow and the **I**nternal circuit (salt bridge) allows **I**ons to flow.

USEFUL TIP

One of the most common salt bridges is potassium nitrate (KNO_3), which consists of K^+ cations and NO_3^- anions.

USEFUL TIP

Cations from the salt bridge flow towards the cathode, and anions flow towards the anode and electrons always flow from the site of oxidation to the site of reduction.

The electrodes and the solutions used in each half-cell vary. Consider the galvanic cell shown in figure 2, where the right half-cell consists of a solid copper (Cu) cathode and copper nitrate solution, $Cu(NO_3)_2$. In this solution, $Cu(NO_3)_2$ is present as dissolved Cu^{2+} cations and NO_3^- anions. Therefore, we call the right half-cell a Cu^{2+}/Cu half-cell. The left half-cell consists of the solid iron (Fe) anode and iron nitrate solution, $Fe(NO_3)_2$. In this solution, $Fe(NO_3)_2$ is present as dissolved Fe^{2+} cations and NO_3^- anions. Similarly, we call the left half-cell a Fe^{2+}/Fe half-cell.

At the cathode, the following reduction reaction occurs:

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

At the anode, the following oxidation reaction occurs:

$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$

Therefore, the following overall reaction can be written.

$Cu^{2+}(aq) + Fe(s) \rightarrow Cu(s) + Fe^{2+}(aq)$

The electrons produced from the oxidation reaction at the anode flow through the wire from the iron anode to the copper cathode, providing a current of electrical energy to light up the LED.

PROGRESS QUESTIONS

Question 2

Which of the following statements is **not** correct about the function of galvanic cells?

A. Electrons migrate via a metal wire connecting the cathode and anode.

B. Negative ions from the salt bridge migrate to the cathode.

C. Ions migrate via the salt bridge connecting the two half-cells.

D. Negative ions from the salt bridge migrate to the anode.

Question 3

Which of the following statements is correct about the redox reactions in primary galvanic cells?

A. The overall reaction is a non-spontaneous reaction.

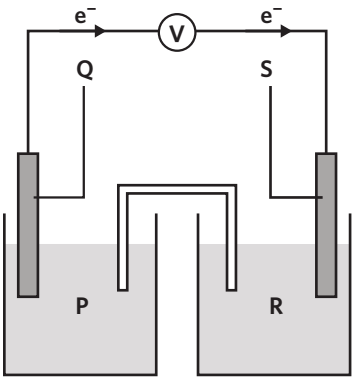
B. The oxidation reaction always occurs at the cathode.

C. The reduction reaction always occurs at the anode.

D. The reduction reaction always occurs at the cathode.

Question 4

A diagram of an electrochemical cell is shown below.



Which of the following gives the correct combination of the electrode in the oxidation half-cell and the electrolyte in the reduction half-cell?

	Electrode (oxidation half-cell)	Electrolyte (reduction half-cell)
A.	S	P
B.	S	R
C.	Q	R
D.	Q	P

VCAA 2020 exam Multiple choice Q3

MISCONCEPTION

'The electrochemical series predicts which redox reactions are spontaneous.'

Even though a redox reaction may be feasible, it will not always be spontaneous due to other factors like high activation energies.

Identifying half-cell reactions in galvanic cells 3.1.15.3

Since redox reactions involve simultaneous reduction and oxidation reactions, it is important to understand which chemical species are undergoing oxidation and which chemical species are undergoing reduction. The **electrochemical series** is a useful guide that can be used to predict which reactions are **feasible**, and which chemical species undergo oxidation or reduction when reacted together.

How can we use the electrochemical series to deduce feasible overall equations from redox half-equations?

The electrochemical series provides a ranking of chemical species in terms of their strengths as oxidising and reducing agents (figure 3). The strongest oxidising agent present, $F_2(g)$, is located at the top left of the table and the strongest reducing agent, Li(s), is located at the bottom-right. This information can be used to predict whether a reaction between two species is feasible under standard conditions and to identify the reactions that may occur. The electrochemical series also shows the standard electrode potential (standard half-cell voltage) for each half-reaction in the right-hand column, which will be covered in more detail in lesson 3D.

Strongest

Oxidising agent

Weakest

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	−0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	−0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	−0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	−0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	−0.44
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	−0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	−0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	−1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	−2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	−2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	−2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	−2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	−3.04

Weakest

Reducing agent

Strongest

Figure 3 VCAA electrochemical series showing the trends in oxidising and reducing strength

USEFUL TIP

When writing half-equations using the electrochemical series, the bidirectional arrow (⇌) must be replaced with a unidirectional arrow (→).

STRATEGY

When predicting which (if any) redox reactions are feasible between species present, it can be helpful to think 'top left/bottom right'. The strongest oxidising agent will be on the left and higher than the strongest reducing agent, which will be lower and on the right.

The strongest oxidising agent present can undergo reduction as per the chemical equation on the electrochemical series and the strongest reducing agent present can undergo oxidation. As the electrochemical series is a list of reduction reactions when read forwards, the equation must be read in reverse for oxidation reactions (figure 4).

A redox reaction will not occur if the strongest oxidising agent present is positioned below the strongest reducing agent present. For example, a redox reaction can occur between $F_2(g)$ and $H_2O(l)$, but not between $O_2(g)$ and $F^-(aq)$. This will be discussed further in chapter 6.

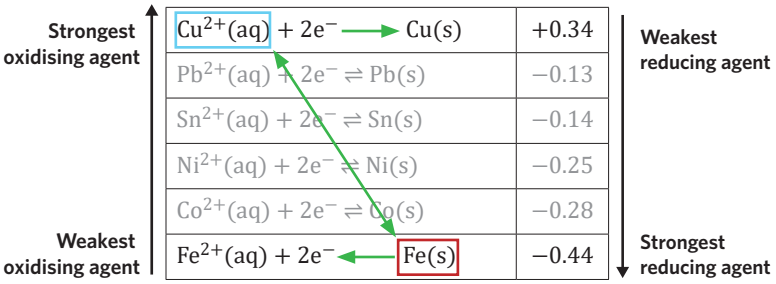


Figure 4 Annotated segment of the electrochemical series

MISCONCEPTION

'Water is not present if it is not specifically mentioned.'

If a species is in an aqueous (aq) state, water will be present and may be involved in the reaction. This state describes a species that is dissolved in water.

WORKED EXAMPLE 1

Consider the diagram of a galvanic cell shown.

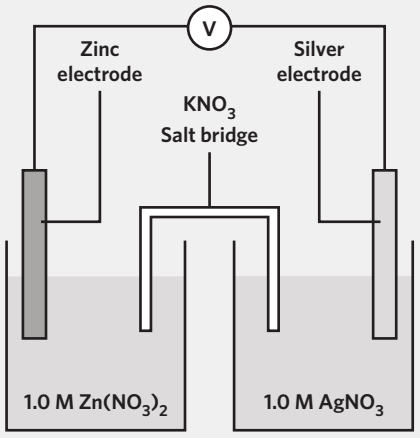
What should be observed at the zinc electrode as the cell operates?

A. No change will be observed at the zinc electrode.

B. The electrode will become thinner and pitted.

C. Crystals will form over the surface of the electrode.

D. Bubbles of gas will form over the surface of the electrode.



What information is presented in the question?

The material of each electrode.

The chemical formula of the electrolyte in each half-cell.

What is the question asking us to do?

Determine the changes that should be observed as this galvanic cell operates.

What strategies do we need in order to answer the question?

1. Outline all species present on the electrochemical series to determine the strongest oxidising agent (top left) and the strongest reducing agent (bottom right).
2. Use this information to determine if/which spontaneous half-reactions will occur in each half-cell.
3. Look at the products and reactants of each reaction to determine any changes that may be observed.

Continues →

Answer

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^-$ → $Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	−0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	−0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	−0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	−0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	−0.44
$Zn^{2+}(aq) + 2e^-$ ← $Zn(s)$	−0.76

$Ag^+(aq)$ is the strongest oxidising agent present (top left) and $Zn(s)$ is the strongest reducing agent present (bottom right).

This means that the half-equations for the reactions in each half-cell will be:

Reduction: $Ag^+(aq) + e^- \rightarrow Ag(s)$

Oxidation: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

From the oxidation equation, it can be observed that solid zinc from the anode will be converted into zinc ions in the solution. This means that over time, this loss of mass will cause the zinc electrode's size to decrease, and cause it to appear thinner and pitted. There is no gas produced, so bubbles will not be observed. Therefore, option B is correct.

VCAA 2014 exam Multiple choice Q28

PROGRESS QUESTIONS

Question 5

A strip of aluminium, Al, is placed in a 1 M calcium nitrate, $Ca(NO_3)_2$, solution under SLC. Which, if any, of the following represent the half-equation for the reduction reaction that occurs.

A. $Ca^{2+}(aq) + 2e^- \rightarrow Ca(s)$

B. $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$

C. $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

D. No reaction occurs.

Question 6

Consider a galvanic cell with standard Cu^{2+}/Cu and Cd^{2+}/Cd half-cells under standard conditions. Which change is predicted to be measurable over time at the cathode?

A. An increase in mass of the cathode

B. A decrease in mass of the cathode

C. An increase in charge of the cathode

D. No change

Limitations of the electrochemical series 3.1.16.1

It is important to be aware of limitations throughout scientific research and experimentation. Scientific models, representations, and experimental methods almost always have limitations that prevent us from seeing the full picture of a concept or mean that an idea is not illustrated in full detail.

What are the limitations of the electrochemical series?

Even though the electrochemical series can tell us which chemical reactions can feasibly occur, it does not provide information about the resulting reaction including:

- Rate of reaction (reaction may occur but be too slow to observe).
- Whether the reaction occurs/can be observed.

Additionally, the electrochemical series can only be used under standard conditions. This means conditions must be as follows:

- temperature of 25 °C (298 K)
- pressure of 100 kPa
- concentration of aqueous reactants of 1 M.

PROGRESS QUESTIONS

Question 7

Which of the following pieces of information is **not** provided by the electrochemical series?

A. Number of electrons transferred in each half-reaction

B. Expected rate of reaction

C. The temperature at which reactions must occur

D. Reduction half-equations

Question 8

A strip of solid zinc, Zn, is placed in a solution containing 0.1 M Pb^{2+} ions at 25 °C and pressure of 100 kPa. Which of the following redox equations represents the reaction that is predicted to occur (if any)?

A. $Pb^{2+}(aq) + 2Zn(s) \rightarrow Zn^{2+}(aq) + 2Pb(s)$

B. $Pb^{2+}(aq) + Zn(s) \rightarrow Zn^{2+}(aq) + Pb(s)$

C. $Pb(s) + Zn^{2+}(aq) \rightarrow Pb^{2+}(aq) + Zn(s)$

D. Cannot be determined from the information provided

Theory summary

- A galvanic cell converts chemical energy to electrical energy using spontaneous redox reactions to provide electrical power to devices.
- Primary cells are non-rechargeable.
- A galvanic cell has the following design features:

Feature	Function
Anode	• Electrode where oxidation occurs • Is negative in a galvanic cell • Must be an electrically conductive material • Can be either an inert or reactive material

Continues →

Feature	Function
Cathode	• Electrode where reduction occurs • Is positive in a galvanic cell • Must be an electrically conductive material • Can be either an inert or reactive material
Electrolyte	• Ionic solution in each half-cell
Salt bridge	• Contains a dissolved ionic solution • Completes the internal circuit • Anions flow to the anode • Cations flow to the cathode • Ionic compound selected must be soluble in water • Ionic compound selected must not react with any other species in the cell • Connects the solutions of two half–cells • Are spectator ions in galvanic cell reactions
Wire	• Allows flow of electrons from the anode to the cathode in a galvanic cell • Forms the external circuit

- The electrochemical series can be used to identify the strongest oxidising agent (top left) and strongest reducing agent (bottom right) present, which will be reduced and oxidised respectively during spontaneous redox reactions.
- The electrochemical series does not show:
  - Rate of reaction (reaction may occur but be too slow to observe).
  - Whether the reaction occurs (only shows which reactions are feasible).
- The electrochemical series is only reliable under Standard Laboratory Conditions (SLC).

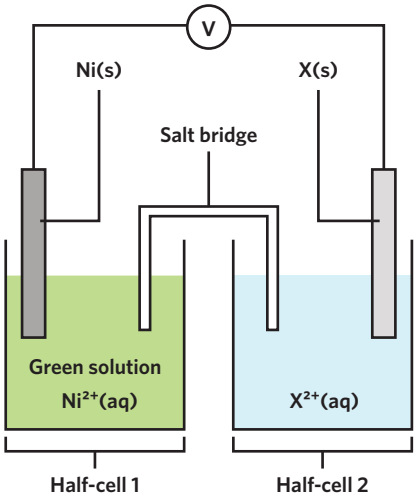
3C Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 9–11.

At the start of the day, a student set up a galvanic cell using two electrodes: nickel, Ni, and metal X. This set-up is shown.



Consider the following alternative metals that could be used to replace metal X:

1. zinc, Zn
2. lead, Pb
3. cadmium, Cd
4. copper, Cu

At the end of the day, the student checked the colour of the solution in Half-cell 1 and observed that the solution was a darker green colour.

Question 9 (1 MARK)

Which of the following is a balanced half-equation showing the oxidation of nickel?

A. $Ni(s) + X^{2+}(aq) \rightarrow Ni^{2+}(aq) + X(s)$

B. $Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

C. $Ni(s) \rightarrow Ni^{2+}(aq) + 2e^-$

D. $Ni^{2+}(aq) + X(s) \rightarrow Ni(s) + X^{2+}(aq)$

Question 10 (1 MARK)

Which of the following lists of metal cations are arranged in order of increasing oxidising ability?

A. $Cu^{2+}, Pb^{2+}, Ni^{2+}, Cd^{2+}, Zn^{2+}$

B. $Zn^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+}$

C. $Cd^{2+}, Cu^{2+}, Pb^{2+}, Ni^{2+}, Zn^{2+}$

D. $Zn^{2+}, Cd^{2+}, Ni^{2+}, Pb^{2+}, Cu^{2+}$

Question 11 (3 MARKS)

Which of the alternative metals could cause the colour of Half-cell 1 to become a darker green?

Explain your answer.

Adapted from VCAA 2019 exam Multiple choice Q5

Exam-style

Question 12 (1 MARK)

Consider the following experiments that are carried out under standard conditions.

Beaker I A strip of nickel metal is placed into a 1.0 M silver nitrate solution.

Beaker II A 1.0 M copper(II) sulfate solution is added to a 1.0 M sodium iodide solution.

Beaker III Chlorine gas is bubbled through a 1.0 M potassium iodide solution.

It would be predicted that a reaction will occur in

A. beaker I only.

B. beaker II only.

C. beakers I and III only.

D. beakers II and III only.

VCAA 2014 exam Multiple choice Q26

Question 13 (4 MARKS)

A particular galvanic cell contains Zn^{2+}/Zn and Ag^+/Ag half-cells. In this case, Zn^{2+} and Ag^+ are present as $Zn(NO_3)_2$ and $AgNO_3$.

Construct a galvanic cell, labelling the following:

- The anode, cathode and their charges
- The material of each electrode and ionic solutions in each half-cell, including states
- The flow of electrons through the external circuit
- The flow of ions in an appropriate salt bridge

Adapted from VCAA 2017 exam Multiple choice Q27

Question 14 (1 MARK)

Some strips of the metals, iron, Fe, zinc, Zn, and silver, Ag, were placed in separate beakers, each containing aqueous 1.0 M nickel(II) sulfate, $NiSO_4$, at 25 °C.

What is expected to occur over time?

A. Ni will be deposited in all of the beakers.

B. Ni will not be deposited in any of the beakers.

C. A reaction will occur only in the beaker containing Ag.

D. A reaction will occur only in the beakers containing Fe and Zn.

VCAA (NHT) 2018 exam Multiple choice Q6

Question 15 (1 MARK)

The following reactions occur in a primary cell battery.

$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2e^-$

$2MnO_2(s) + 2e^- + H_2O(l) \rightarrow Mn_2O_3(s) + 2OH^-(aq)$

Which one of the following statements about the battery is correct?

A. The reaction produces heat, and Zn reacts directly with MnO_2.

B. The reaction produces heat, and Zn does not react directly with MnO_2.

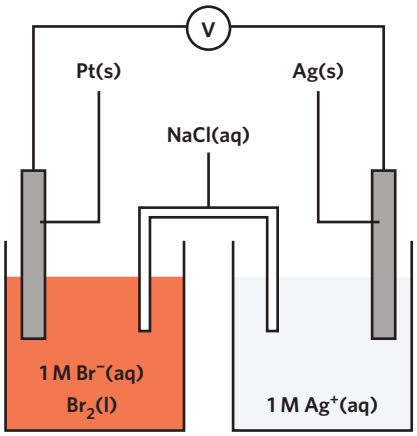
C. The reaction does not produce heat, and Zn reacts directly with MnO_2.

D. The reaction does not produce heat, and Zn does not react directly with MnO_2.

VCAA 2020 exam Multiple choice Q26

Question 16 (7 MARKS)

Chemistry student Inès is trying to construct a functional galvanic cell. For her first attempt, she creates the cell shown.



a. After connecting the two half cells with a wire, Inès soon discovers that the galvanic cell is not operating as expected, and that a precipitate is forming at the bottom of one half-cell. Explain this observation. 2 MARKS

b. In light of this, Inès removed the salt bridge entirely, but noticed that no electricity was generated. Why did this happen? 2 MARKS

c. Suggest an appropriate salt bridge Inès could use instead, and give two reasons why it would be an appropriate choice. 3 MARKS

Question 17 (2 MARKS)

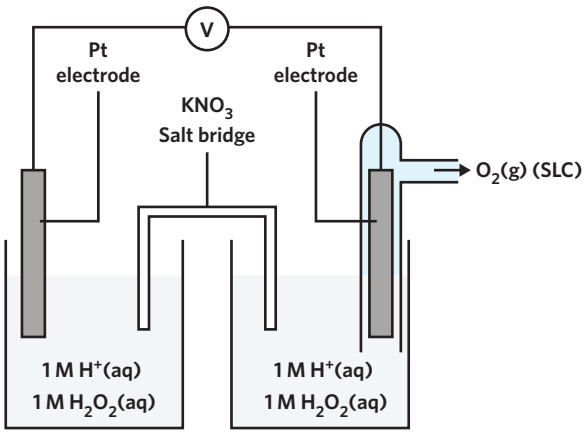
Chemistry student Emilia is studying redox reactions. They initially had a beaker with a 1.0 M blue solution of $Cu^{2+}(aq)$ ions and accidentally put a strip of Pb(s) and Fe(s) in the beaker instead of only Pb(s). Emilia predicted that the following reaction would still occur.

$Cu^{2+}(aq) + Pb(s) \rightarrow Cu(s) + Pb^{2+}(aq)$

Is Emilia's prediction accurate? If they are incorrect, write the overall redox reaction that should occur.

Question 18 (3 MARKS)

A student plans to construct the following galvanic cell.



a. Write the half-equations for the predicted half-cell reactions in this galvanic cell. 2 MARKS

b. The student assembles this galvanic cell, but does not observe a reaction. Suggest a possible reason why. 1 MARK

Adapted from VCAA 2013 exam Multiple choice Q25

Key science skills

Question 19 (7 MARKS)

Chemistry student Bruno wants to investigate the reactions of different metals, Ag, Zn, and Al, in 1 M copper(II) nitrate, $Cu(NO_3)_2$.

a. Why should Bruno complete a risk assessment before undertaking this experiment? 2 MARKS

b. Bruno creates the risk assessment shown, but has forgotten to include something. Solid silver and aluminium are not hazardous, so have been left out intentionally. Identify the mistake Bruno has made, and explain why this should not be left out. 2 MARKS

Chemical/Material	Risk	Precaution
200 mL beaker	• Breakage of beaker • Cuts from chipped rims	• Discard any chipped or cracked beakers. • Use a dustpan and brush to clean up broken glass.
1 M copper(II) nitrate, $Cu(NO_3)_2(aq)$	• Toxic if swallowed • Causes skin irritation • Causes serious eye irritation • Very toxic to aquatic life	• Wear protective gloves and lab coat when handling. • Dispose of in a copper waste container.
Zinc, Zn(s)	• Toxic to aquatic life	• Dispose of appropriately in rubbish bin.

c. Bruno accidentally pours some of the beaker of zinc nitrate produced during the experiment down the sink instead of into the appropriate disposal container. Zinc nitrate is very dangerous to aquatic life. What should he do? 1 MARK

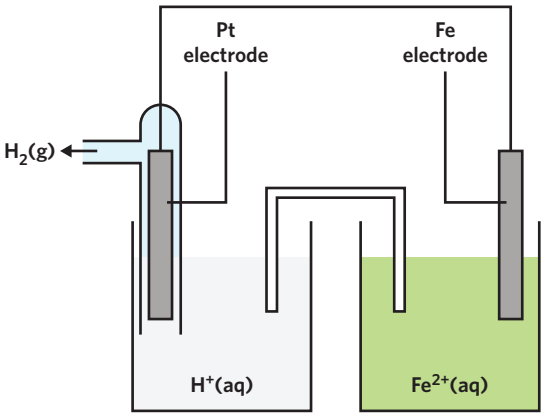
d. Bruno observes that some of the metals used are either only slightly corroded, or completely undamaged. Suggest what Bruno should do with these rods after the experiment has been completed to abide by green chemistry principles. 2 MARKS

FROM LESSON 12B

Questions from multiple lessons

Question 20 (1 MARK)

A diagram of a galvanic cell is shown.



For the reaction in this galvanic cell

A. $H^+(aq)$ is the oxidising agent.

B. $H^+(aq)$ is the reducing agent.

C. $H_2(g)$ is the oxidising agent.

D. $H_2(g)$ is the reducing agent.

VCAA (NHT) 2022 exam Multiple choice Q12

FROM LESSON 3A

Question 21 (6 MARKS)

A chemist constructed a Daniell cell, which consists of standard Zn^{2+}/Zn and Cu^{2+}/Cu half-cells. It was allowed to run until the zinc anode appeared corroded, and crystals were visible on the copper cathode. The zinc anode was weighed before and after the cell was run, and it was found that its mass decreased by 1.403 g.

a. Based on this information, how many moles of Zn(s) reacted? 2 MARKS

b. Write the overall equation for the redox reaction that occurs in this cell. 1 MARK

c. Based on the overall galvanic cell reaction, how many grams of copper are predicted to have formed as crystals on the cathode? 3 MARKS

FROM LESSON 2A

3D Designing galvanic cells

STUDY DESIGN DOT POINT

- the use and limitations of the electrochemical series in designing galvanic cells and as a tool for predicting the products of redox reactions, for deducing overall equations from redox half-equations and for determining maximum cell voltage under standard conditions

3A 3B 3C **3D** 3E 3F 3G

- 3.1.16.2 Designing half-cells
- 3.1.16.3 Constructing a complete galvanic cell
- 3.1.16.4 Predicting and determining maximum cell voltage

ESSENTIAL PRIOR KNOWLEDGE

3C Electrochemical series

3C Primary galvanic cells

See questions 22–23.

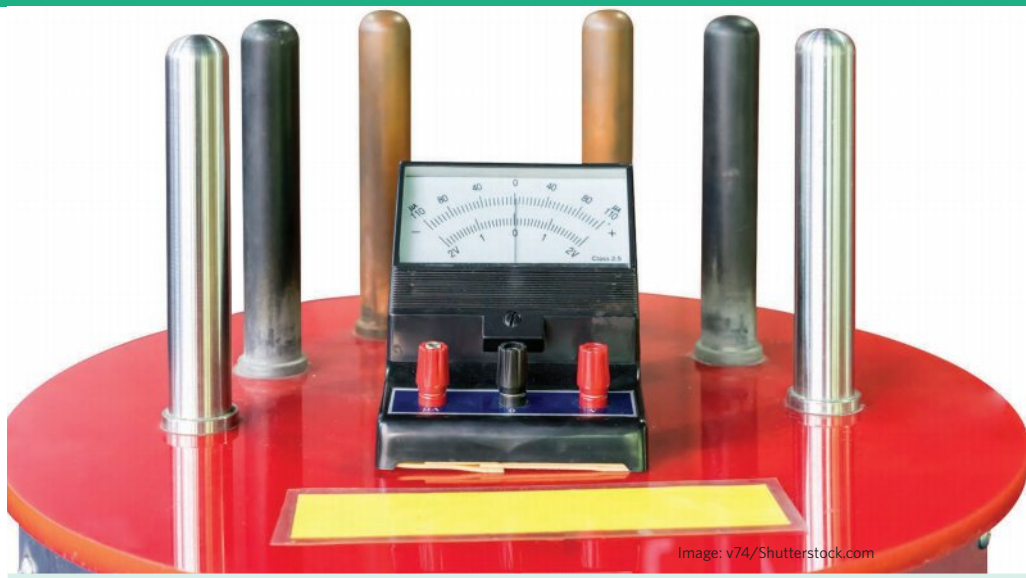


Image: v74/Shutterstock.com

How can a galvanic cell be used to investigate the conductivity of humans?

Scientists have been able to analyse changes in the **cell voltage** of galvanic cells in order to investigate the conductivity of humans. In this lesson, we will investigate how galvanic cells are designed to fit particular purposes and conditions, and learn how to predict and determine maximum cell **voltage**.

KEY TERMS AND DEFINITIONS

Cell voltage voltage produced between the anode and cathode of an electrochemical cell

Standard electrode potential (E^0) potential of a half-cell reaction, given in volts (V), relative to the Standard Hydrogen Electrode

Standard Hydrogen Electrode (SHE) standard $H^+(aq)/H_2(g)$ half-cell with standard electrode potential 0.00 V, which the electrochemical series is created with respect to

Voltage (V) the potential difference in energy per unit charge between two points

Designing half-cells 3.1.16.2

Half-cells can be designed to have a variety of different reactants. The states of the reactants and the species themselves must be considered when selecting appropriate electrodes.

How can different types of half-cells be constructed?

Galvanic cells can be constructed so that half-reactions take place between either:

- a metal and an (aqueous) ion,
- an (aqueous) ion and an (aqueous) ion,
- or a gas and an (aqueous) ion.

If a half-cell's half-reaction involves a metal reacting with ions in a solution, the metal serves as the electrode, as it is a solid, conductive material. However, when a half-cell involves the half-reaction between ions in a solution or a gas with ions in a solution, an inert electrode must be used, as discussed in lesson 3C.

These inert electrodes must:

- not react with any species in its half-cell
- be solid
- be electrically conductive.

If a half-reaction involves a gaseous reactant, a special half cell has to be used involving an inert electrode (platinum or carbon) and a glass tube to direct the movement of the gas. Gas is pumped into the glass tube at 100 kPa (SLC) and onto the electrode to be either oxidised or reduced. The most common gaseous half cell is the **Standard Hydrogen Electrode (SHE)**, which is shown in figure 1. This half-cell reaction has a **standard electrode potential (E^0)** value of 0.00 V, which all other half-cells are measured relative to. This will be explored further later in this lesson.

In figure 1, the bottom of the platinum electrode is covered in a substance known as platinum black. Platinum black is a fine powdery substance that increases the surface area of the electrode, meaning that hydrogen gas reacts at a higher rate. This will be covered in greater detail in lesson 4A.

In this case, if reduction takes place in the half cell under acidic conditions, hydrogen ions in the solution are converted into hydrogen gas:

$2H^+(aq) + 2e^- \rightarrow H_2(g)$

If oxidation takes place in the half cell under acidic conditions, hydrogen gas is converted to hydrogen ions in the solution:

$H_2(g) \rightarrow 2H^+(aq) + 2e^-$

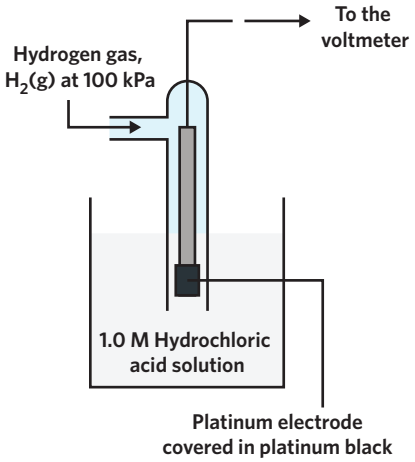


Figure 1 Standard Hydrogen Electrode

PROGRESS QUESTIONS

Question 1

What is a suitable material for the electrode in the Fe^{2+}/Fe^{3+} standard half cell?

A. Fe(s)

B. Zn(s)

C. Pt(s)

D. Na(s)

Constructing a complete galvanic cell 3.1.16.3

Galvanic cells must be designed to not react adversely with species in the surroundings, be economical, be relatively safe for use, and not be damaging to the environment. Designing batteries to produce a desired voltage will be discussed later in this lesson. In this section, we will focus on galvanic cells designed for specific purposes and the conditions under which they operate.

How are primary galvanic cells designed for specific purposes and conditions?

When designing galvanic cells for use in devices, as with any chemical process in industry, it is crucial to consider:

- species in the environment that may interfere with a galvanic cell's function[1]
- products, reactants, and potential malfunctions that may be dangerous to humans[2]
- environmental impacts[3]
- ability to source materials
- economic factors.

KEEN TO INVESTIGATE?

[1] **Why should most batteries be kept away from water?**
Search: Can lithium batteries get wet?

KEEN TO INVESTIGATE?

[2] **Why are button cells so dangerous?**
Search: coin and button batteries (cells) coin or button?

KEEN TO INVESTIGATE?

[3] **Why is the use of mercury in batteries regulated?**
Search: Minamata Convention on Mercury Australia

KEEN TO INVESTIGATE?

[4] **Why do used batteries have to be separately recycled?**
Search: Drop off used batteries for recycling – Sustainability Victoria

MISCONCEPTION

'All metal ions can be extracted from solutions under standard conditions.'

Metal ions below water in the electrochemical series (weaker oxidising agents than water) cannot be extracted from solutions under standard conditions. This will be explored in further detail in lesson 6A.

Although risks associated with battery use cannot always be completely mitigated, regulations can be created regarding their production, use, and disposal to increase their safety.[4]

In VCE chemistry, we focus primarily on aspects of the surroundings, and properties of an individual cell, that may affect its function. Be aware of the following when designing, constructing, and evaluating primary galvanic cells:

- When water is present (even as a solution with (aq) state), it is available to react.
- Exposure to air implies that oxygen is available to react. However, in VCAA exams, half-equations involving oxygen must only be considered in primary galvanic cells where oxygen is bubbled into a half-cell at SLC.
- Appropriate salt bridges and electrodes must be selected. This is explored in lesson 3C.
- The electrochemical series is only reliable under standard conditions and for standard half-cells.
- Rate of reaction may be too slow for a reaction to be observed. The conditions under which the reaction occurs can be adjusted to increase this, which will be covered in lesson 4A.

WORKED EXAMPLE 1

A galvanic cell is constructed such that one half-cell contains a Mn(s) electrode in 1.0 M $Mn^{2+}(aq)$, and the other half-cell contains a Mg(s) electrode in 1.0 M $Mg^{2+}(aq)$. Assume that this cell operates under standard conditions. Chemistry student Jack predicts that the following half-reactions will occur.

Reduction: $Mn^{2+}(aq) + 2e^- \rightarrow Mn(s)$

Oxidation: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$

What has Jack not considered when making his prediction? Make your own prediction based on your answer.

What information is presented in the question?

Mn(s), $Mn^{2+}(aq)$, Mg(s), $Mg^{2+}(aq)$, and water, $H_2O(l)$, are all available to react.

What is the question asking us to do?

Determine what Jack has not considered when making his prediction.

Suggest our own predicted reduction and oxidation half-equations for this cell.

What strategies do we need in order to answer the question?

1. Water must be considered as a potential reactant when a solution is present (species in aqueous (aq) state).
2. The strongest oxidising agent present can feasibly react with the strongest reducing agent present.
3. Outline species on the electrochemical series to determine the strongest oxidising agent present (top left) and the strongest reducing agent present (bottom right).
4. The oxidation reaction will proceed in the opposite direction to which it appears in the electrochemical series.

Answer

Jack has not considered that water is present and available to react.

Water is present in each half-cell, as each half-cell contains ions dissolved in a solution ($Mg^{2+}(aq)$ and $Mn^{2+}(aq)$). According to the electrochemical series, water is the strongest oxidising agent present, and magnesium, Mg, is the strongest reducing agent present. Therefore, H_2O will be reduced in one half-cell, and Mg will be oxidised in the other half-cell.

$2H_2O(l) + 2e^- \longrightarrow H_2(g) + 2OH^-(aq)$	−0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	−1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^- \longleftarrow Mg(s)$	−2.37

Therefore, the following half-reactions are predicted.

Reduction: $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

Oxidation: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$

Although the current VCE study design does not require knowledge of specific types of batteries, the following primary cells demonstrate how primary cells are designed for specific purposes and conditions.

Lithium-iodine batteries

Primary cells are used in pacemakers as these devices are unable to be recharged while implanted in the body for long periods of time. Lithium-iodine batteries (figure 2) are often used in pacemakers due to their high energy density and longevity; they can last up to 10 years before needing to be replaced.

As lithium reacts explosively with water, it is unsafe for the lithium cathode to come into contact with any potential electrolyte used in its half-cell. Instead, lithium is suspended in graphite, which is able to conduct charge and facilitate the flow of Li^+ ions through a separator (salt bridge) towards the cathode. As the cell does not use any gaseous reactants or produce any gaseous products, airtight casing can contain the battery. Typically, a titanium casing is used as it does not react with species in the human body unless under extreme temperatures.

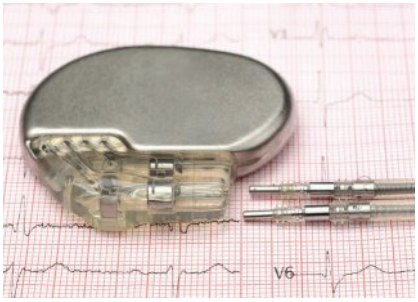


Image: Swapan Photography/Shutterstock.com

Figure 2 Lithium-iodine battery in titanium casing for use as a pacemaker for a human heart

Zinc-air cell

Zinc-air cells (figure 3) are often used to power hearing aids. When they are activated, they take in air (including oxygen), allowing zinc to react at the anode, and oxygen to react at the cathode. These cells use an alkaline electrolyte. In hearing aids, the zinc-air cell operates under non-extreme conditions, meaning the following half-reactions occur.

Reduction: $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$

Oxidation: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

The use of an air half-cell allows this battery to be relatively light and inexpensive, making it an appropriate choice to power hearing aids.

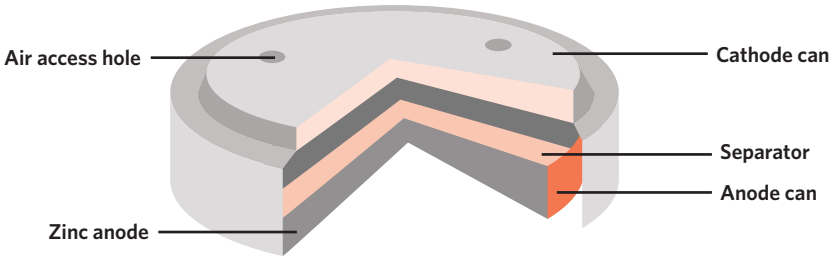


Figure 3 Design of zinc-air cell

Alkaline batteries

Standard AA and AAA batteries are alkaline cells that use zinc and manganese dioxide electrodes, as well as an alkaline electrolyte. These materials are relatively stable under non-extreme conditions, have high energy density, and are inexpensive to manufacture. They operate according to the half-equations:

Reduction: $2MnO_2 + H_2O + 2e^- \rightarrow Mn_2O_3 + 2OH^-$

Oxidation: $Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$

Their structure is shown in figure 4.

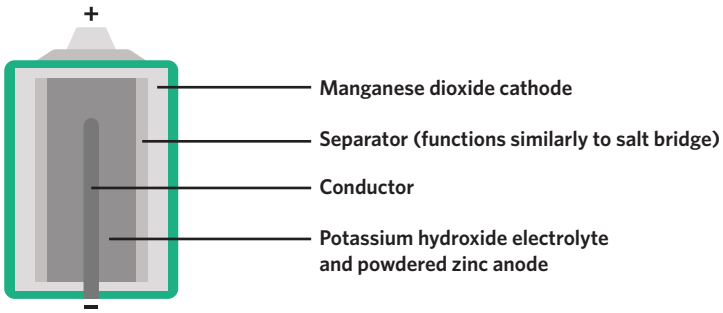
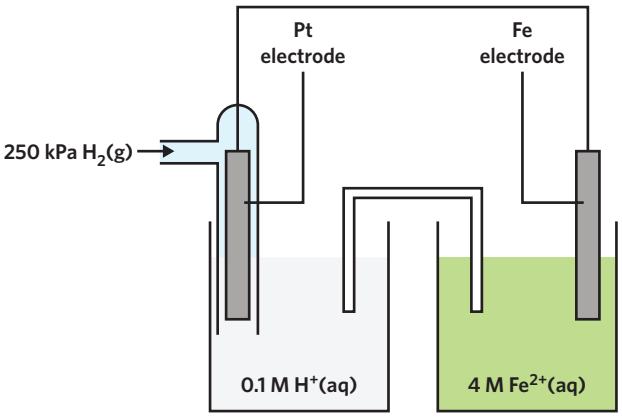


Figure 4 Design of an alkaline battery

PROGRESS QUESTIONS

Question 2

Consider the following galvanic cell.



Which reaction occurs at the cathode?

A. $H_2(g) \rightarrow 2H^+(aq) + 2e^-$

B. $2H^+(aq) + 2e^- \rightarrow H_2(g)$

C. $Fe^{2+}(aq) + 2e^- \rightarrow Fe(s)$

D. Cannot be determined from the information provided.

Question 3

Which of the following represents standard conditions for a standard half cell?

A. 1.0 M, 100 kPa, and 298 K

B. 1.0 M, 100 kPa, and 273 K

C. 1.0 M, 1 atm and 298 K

D. 1.0 M, 1 atm and 273 K

Predicting and determining maximum cell voltage 3.1.16.4

Batteries, including galvanic cells, are designed to operate at a particular voltage. The electrochemical series can be a useful tool in predicting and determining the maximum cell voltage of primary galvanic cells.

MISCONCEPTION

'The electrochemical series can be used to predict the exact voltage produced by a galvanic cell.'

The electrochemical series helps us predict the maximum cell voltage produced by a galvanic cell under standard conditions. In practice, some energy is lost as heat, at times resulting in a lower cell voltage than predicted.

USEFUL TIP

You may also see voltage referred to as 'potential difference'.

How can we determine the voltage produced in a galvanic cell?

The electrochemical series can also be used to predict the maximum voltage (in volts, V), able to be produced between two electrodes in a galvanic cell based on the half-reactions occurring under standard conditions. For every half-equation in the electrochemical series, there is a corresponding E^0 value in the right column, which represents the standard electrode potential, E^0, of the half-reaction with respect to the standard hydrogen electrode (SHE). For this reason, the SHE has an E^0 value of 0.00 V.

Even though E^0 values can be positive or negative, the voltage between electrodes (cell voltage) should always be written as a positive value. Using these values, the maximum voltage produced between the anode and cathode of a galvanic cell can be calculated as follows.

$$E_{cell} = E^0 \text{ of reduction reaction} - E^0 \text{ of oxidation reaction}$$

or $$E_{cell} = \text{most positive value} - \text{least positive value}$$

WORKED EXAMPLE 2

A galvanic cell with Zn/Zn^{2+} and Cu/Cu^{2+} half-cells is known as a Daniell cell.
What are the half-equations of the reduction and oxidation reactions that occur in this cell?
Use this information to determine the cell voltage of a Daniell cell under standard conditions.

What information is presented in the question?

The conjugate redox pair of one half-reaction is Zn(s) and $Zn^{2+}(aq)$.

The conjugate redox pair of the other half-reaction is Cu(s) and $Cu^{2+}(aq)$.

What is the question asking us to do?

Write the oxidation and reduction half-equations for this cell.

Calculate the maximum voltage that can be created across the electrodes of this cell.

What strategies do we need in order to answer the question?

1. Outline all species present on the electrochemical series to determine the strongest oxidising agent (top left) and the strongest reducing agent (bottom right).
2. Write down the corresponding reduction and oxidation half-equations from the electrochemical series.
3. The oxidation reaction on the electrochemical series proceeds in reverse, so read it backwards.
4. Subtract the E^0 value of the oxidation reaction (least positive) from the E^0 value of the reduction reaction (most positive) to find the maximum voltage in volts.

Answer

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	−0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	−0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	−0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	−0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	−0.44
$Zn^{2+}(aq) + 2e^- \leftarrow Zn(s)$	−0.76

$Cu^{2+}(aq)$ is the strongest oxidising agent present (top left) and Zn(s) is the strongest reducing agent present (bottom right).

This means that the half-equations for the reactions in each half-cell will be:

Reduction: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

Oxidation: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

To calculate the maximum cell voltage:

$E_{cell} = E^0$(oxidising agent half-cell) $- E^0$ (reducing agent half-cell)

$E_{cell} = +0.34\ V - (-0.76\ V)$

$E_{cell} = +1.10\ V$

The cell voltage of a galvanic cell can be measured by connecting a voltmeter, which measures voltage, or a multimeter, which measures both voltage and current to each electrode.

PROGRESS QUESTIONS

Question 4

Four standard galvanic cells are set up as indicated below.

Cell I a Br_2/Br^- standard half-cell connected to a Cu^{2+}/Cu standard half-cell

Cell II an Sn^{2+}/Sn standard half-cell connected to a Zn^{2+}/Zn standard half-cell

Cell III a Br_2/Br^- standard half-cell connected to an I_2/I^- standard half-cell

Cell IV a Co^{2+}/Co standard half-cell connected to an Fe^{3+}/Fe^{2+} standard half-cell

Which cell would be expected to develop the largest potential difference?

A. I

B. II

C. III

D. IV

VCAA 2013 exam Multiple choice Q26

How can we design galvanic cells to produce a particular voltage?

Different devices may require different voltages to run. For example, a simple analogue watch may require a 1.5 V button cell, whereas alkaline batteries are available that produce up to 12 V, which are recommended for devices such as long-distance remote controls and security systems.

At standard conditions, the electrochemical series can be used to construct primary galvanic cells that are predicted to operate at a desired voltage. This predicted voltage will be the difference between the E^0 values assigned to each half-reaction in the electrochemical series.

WORKED EXAMPLE 3

A chemistry student wants to create a galvanic cell that is predicted to produce a voltage of +0.59 V at standard conditions. They know that one half-cell will be a Cu^{2+}/Cu half-cell and the copper electrode will be the cathode. Choose an appropriate second half-cell to produce the desired voltage.

What information is presented in the question?

The desired voltage is +0.59 V.

The cell will contain a Cu^{2+}/Cu half-cell.

What is the question asking us to do?

Choose an appropriate half-cell to be connected to the Cu^{2+}/Cu half-cell, so that the cell produces +0.59 V.

What strategies do we need in order to answer the question?

1. Use the desired voltage and standard electrode potential of the Cu^{2+}/Cu half-cell to calculate the standard electrode potential of the second half-cell.
2. Write all E^0 values with the correct sign (+ or −).

Answer

According to the electrochemical series, the standard electrode potential of the standard Cu^{2+}/Cu half-cell is +0.34 V.

The difference between this value and the standard electrode potential of the second half-cell will be +0.59 V. Therefore,

$E_{cell} = E^0(Cu^{2+}/Cu \text{ half-cell}) - E^0(\text{second half-cell})$

$+0.59 \text{ V} = +0.34 \text{ V} - E^0(\text{second half-cell})$

$E^0(\text{second half-cell}) = -0.25 \text{ V}$

Using the electrochemical series, the nickel half-cell reaction shown has a standard electrode potential of −0.25 V:

$Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

Therefore, the Ni^{2+}/Ni half-cell is an appropriate choice to complete this galvanic cell.

PROGRESS QUESTIONS

Question 5

Which of the following half-cells would be able to be connected to a Sn^{4+}/Sn^{2+} half-cell to create a voltage of +0.62 V?

A. Fe^{3+}/Fe^{2+}

B. I_2/I^-

C. Fe^{2+}/Fe

D. Al^{3+}/Al

How can we use voltage to determine relative oxidising and reducing strengths?

The relative oxidising and reducing strengths of various half-cell compositions can be determined by connecting them to form a galvanic cell. This was how the electrochemical series was created; each standard half-cell was connected to the standard hydrogen electrode (SHE) and the cell voltage was measured using a voltmeter at standard conditions.

We can use the voltage recorded in different half-cells and observations of the cell as the reaction occurs to determine the relative oxidising and reducing strengths of different half-cells under consistent conditions.

WORKED EXAMPLE 4

A student aims to investigate the reaction of different metals in an Sn^{2+} solution under standard conditions. It is observed that:

- A strip of iron, Fe, placed in the solution appears to form a grey coating.
- No reaction was observed when a strip of copper, Cu, was left in the solution overnight.

Using this information, rank the predicted standard electrode potentials of the following redox half-reactions from highest to lowest.

$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$

$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$

$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$

What information is presented in the question?

A reaction is observed between Fe and Sn^{2+}.

No reaction is observed between Cu and Sn^{2+}.

What is the question asking us to do?

Rank the electrode potentials of the half-reactions provided from highest to lowest.

What strategies do we need in order to answer the question?

1. The electrochemical series provides a list of standard redox half-equations.
2. The standard electrode potential of the reduction half-reaction must be higher than the standard electrode potential of the oxidation half-reaction.

Answer

The strip of iron is observed to form a grey coating.
This suggests that Sn^{2+} is reduced to form Sn while Fe is oxidised to form Fe^{2+}, meaning that the tin half-reaction is predicted to have a higher standard electrode potential than the iron half-reaction.

No reaction is observed between Cu and Sn^{2+}.
This indicated that the Sn^{2+} is a weaker oxidising agent than solid copper's conjugate, Cu^{2+}, meaning that the tin half-reaction is predicted to have a lower standard electrode potential than the copper half-reaction. Therefore, the following ranking can be constructed.

$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$ Highest E^0

$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$ ↓

$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$ Lowest E^0

WORKED EXAMPLE 5

A student constructs a galvanic cell with a copper anode. The contents of the reduction half-cell are unknown. Based on the standard electrode potentials of the following half-reactions, which half-reaction could feasibly occur at the cathode under standard conditions? Assume that both half-cells are standard. States are not required.

$S_4O_6^{2-} + 2e^- \rightleftharpoons 2S_2O_3^{2-}$ $+0.17$ V

$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$ $+1.61$ V

$PbSO_4 + 2e^- \rightleftharpoons Pb + SO_4^{2-}$ -0.31 V

What information is presented in the question?

Copper reacts at the anode of this half-cell.

The unknown reaction occurs at the cathode.

The reduction half-equations for each set of potential half-cell contents.

The standard electrode potentials for each potential half-cell reaction.

What is the question asking us to do?

Write the reduction equation that occurs at the cathode in an appropriately selected half-cell.

What strategies do we need in order to answer the question?

1. The standard electrode potential of the reaction at the anode must be lower than that of the reaction at the anode.
2. Use the electrochemical series to find the standard electrode potential of copper.
3. The equation containing the strongest reducing agent will have the lowest E^0 value.
4. Oxidation is the gain of one or more electrons.

Answer

According to the electrochemical series in the VCE Data Book, the standard electrode potential of the standard Cu^{2+}/Cu half-cell is $+0.34$ V. Using this information, a 'mini' electrochemical series can be created.

$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$ $+1.61$ V

$Cu^{2+} + 2e^- \rightleftharpoons Cu$ $+0.34$ V

$S_4O_6^{2-} + 2e^- \rightleftharpoons 2S_2O_3^{2-}$ $+0.17$ V

$PbSO_4 + 2e^- \rightleftharpoons Pb + SO_4^{2-}$ -0.31 V

This can be read much like the VCE Data Book's electrochemical series; the oxidation half-reaction (lower standard electrode potential) must be positioned below the reduction half-reaction (higher standard electrode potential). Therefore, the highest positioned reaction is the only reduction half-reaction that could feasibly occur while copper is oxidised at the anode under standard conditions. The reduction half-equation for this reaction is

$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$

Note that as the electrochemical series provides a list of reduction reactions, the half-equation of this reduction reaction can be copied directly, with the bidirectional arrow changed to a unidirectional arrow. If the question requested an oxidation half-reaction, the reaction would proceed in the opposite direction.

PROGRESS QUESTIONS

Question 6

Consider the following half-equation.

$ClO_2(g) + e^- \rightleftharpoons ClO_2^-(aq)$

It is known that:

- $ClO_2(g)$ will oxidise HI(aq), but not HCl(aq).
- $Fe^{3+}(aq)$ will oxidise HI(aq), but not $NaClO_2(aq)$.

Based on this information, $Fe^{2+}(aq)$ can be oxidised by

A. $Cl_2(g)$ and $I_2(s)$.

B. $Cl_2(g)$, but not $ClO_2(g)$.

C. $ClO_2(g)$ and $Cl_2(g)$, but not $I_2(s)$.

D. $Cl_2(g)$, $ClO_2(g)$, and $I_2(s)$.

VCAA 2020 exam Multiple choice Q30

Theory summary

- If a half-cell only contains liquid and/or gaseous reactants, an inert electrode must be used.
- An inert electrode must
  - not react with any species in its half-cell
  - be solid
  - be electrically conductive.
- Water must be considered as a potential reactant whenever a solution (species in aqueous (aq) state) is present.
- The electrochemical series provides a ranking of half-reactions in terms of decreasing standard electrode potentials.
- $E_{cell} = E^0$ of reduction reaction (most positive) $- E^0$ of oxidation reaction (least positive)

3D Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

A zinc-carbon dry cell battery is found to produce a voltage of +1.50 V, measured at standard conditions.

The two half-reactions that occur in this battery are shown in the following equations.

Equation 1: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

Equation 2: $MnO_2(s) + H_2O(l) + e^- \rightarrow MnO(OH)(s) + OH^-(aq)$

Question 7 (1 MARK)

What is the standard electrode potential of the Zn^{2+}/Zn half-cell?

A. +0.76 V

B. −0.76 V

C. +0.15 V

D. −0.15 V

Question 8 (1 MARK)

Which one of the following statements is true?

A. The E^0 value for the reduction half-cell is less positive than the E^0 value for the oxidation half-cell.

B. The E^0 value for the reduction half-cell is more positive than the E^0 value for the oxidation half-cell.

C. The E^0 value for the reduction half-cell is double the E^0 value for the oxidation half-cell.

D. The E^0 value for the reduction half-cell is half the E^0 value for the oxidation half-cell.

Question 9 (1 MARK)

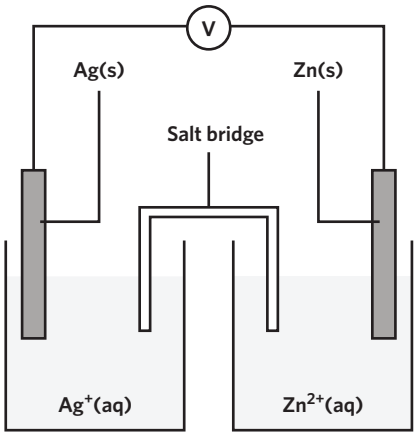
Assuming standard conditions, what is the standard electrode potential of Equation 2?

VCAA (NHT) 2018 exam Multiple choice Q15

Exam-style

Question 10 (1 MARK)

A galvanic cell set up under standard conditions is shown below.



The cathode material in this cell and the maximum voltage produced by this cell (under standard conditions) are respectively

A. Ag and +0.16 V

B. Ag and +1.56 V

C. Zn and +0.16 V

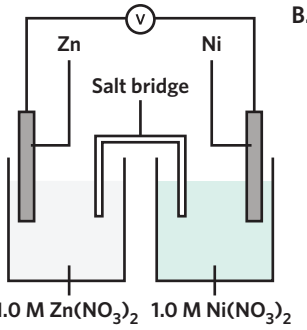
D. Zn and +1.56 V

VCAA 2012 Exam 2 Multiple choice Q18

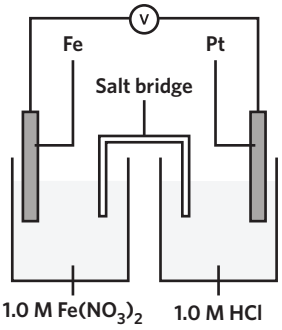
Question 11 (1 MARK)

Which one of the following galvanic cells will produce the largest cell voltage under standard laboratory conditions (SLC)?

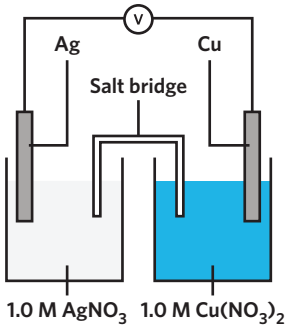
A.



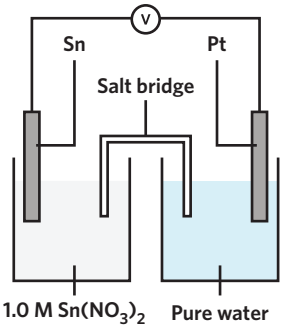
B.



C.



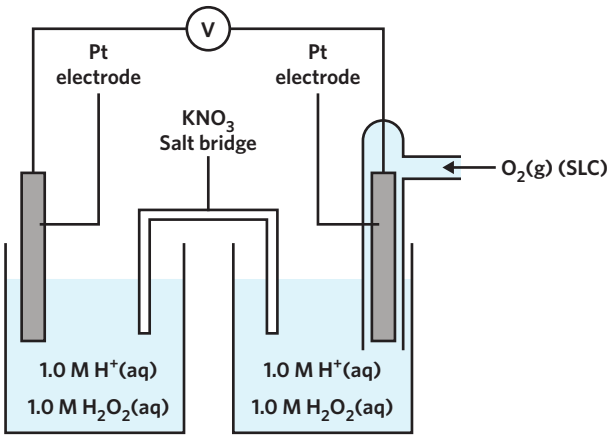
D.



VCAA 2019 exam Multiple choice Q18

Question 12 (1 MARK)

A student constructs the following galvanic cell.



The student predicts that the following overall reaction will occur.

$2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g)$

However, no reaction is observed.

This is most likely because

A. the difference between the E^0 values is too small for a reaction to occur.

B. hydrogen peroxide will oxidise water in preference to itself.

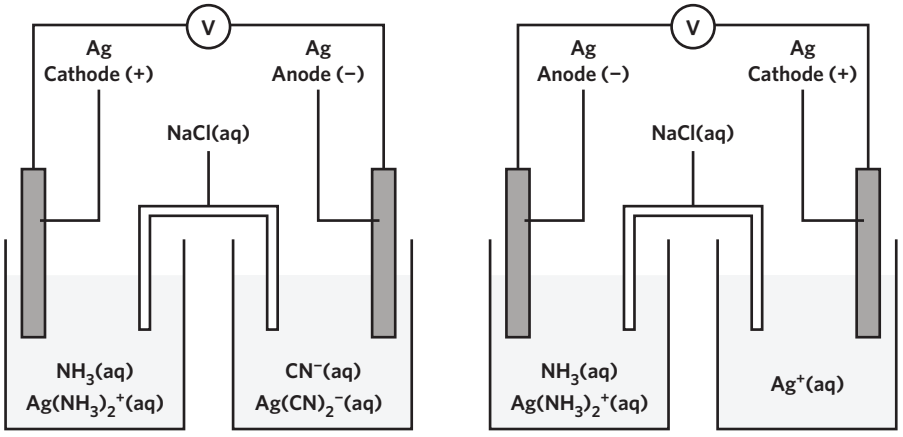
C. the student did not construct standard half-cells.

D. the rate of the reaction is extremely slow.

VCAA 2013 exam Multiple choice Q25

Question 13 (1 MARK)

Two galvanic cells were constructed under standard conditions in an experiment to determine the relative positions in the electrochemical series of the standard electrode potential, E^0, for the following reactions. Both cells generate a voltage.



$Ag(NH_3)_2^+(aq) + e^- \rightleftharpoons Ag(s) + 2NH_3(aq)$ $\quad E^0_1$

$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$ $\quad E^0_2$

$Ag(CN)_2^-(aq) + e^- \rightleftharpoons Ag(s) + 2CN^-(aq)$ $\quad E^0_3$

The values of the electrode potentials in order from highest to lowest would be

A. E^0_1, E^0_2, E^0_3

B. E^0_1, E^0_3, E^0_2

C. E^0_2, E^0_1, E^0_3

D. E^0_3, E^0_2, E^0_1

VCAA 2011 Exam 2 Multiple choice Q10

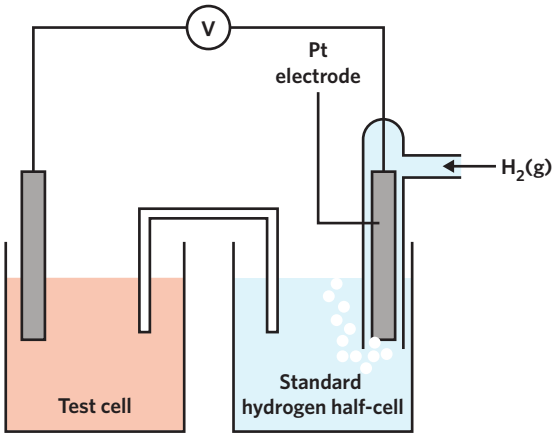
Question 14 (3 MARKS)

In a problem-solving activity, a student is given the following information regarding three half-equations. However, although the three numerical values of E^0 are correct, they have been incorrectly assigned to the three half-equations.

Half-equation	E^0
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	−0.83 V
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	−0.74 V
$Cr^{3+}(aq) + 3e^- \rightleftharpoons Cr(s)$	+0.34 V

The objective of this task is to correctly assign the E^0 values to the corresponding half-equation.

To do this, the student constructs standard half-cells for each of the above half-reactions. These half-cells are connected, one at a time, to a standard hydrogen half-cell as indicated in the diagram below.



The following observations were made either during or after the electrochemical cell discharged electricity for several minutes.

Experiment	Half-cell reaction being investigated	Experimental notes
1	$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	Electron flow was detected passing from the standard hydrogen half-cell to the half-cell containing the copper electrode.
2	$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	The pH of the solution in the standard hydrogen half-cell increased.
3	$Cr^{3+}(aq) + 3e^- \rightleftharpoons Cr(s)$	The mass of the chromium electrode decreased.

a. The above information can only be used to assign **one** of the E^0 values to its corresponding half-equation. Identify this half-equation by assigning the correct E^0 value to its corresponding half-equation in the table below. 1 MARK

Half-equation	E^0
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	
$Cr^{3+}(aq) + 3e^- \rightleftharpoons Cr(s)$	

b. Explain why the other two E^0 values cannot be correctly assigned to their half-equation. 1 MARK

c. Explain why the pH of the solution in the standard hydrogen half-cell increased in experiment 3. 1 MARK

Adapted from VCAA 2010 Exam 2 Short answer Q6

Question 15 (3 MARKS)

Moussa was creating a galvanic cell using platinum electrodes and a $KNO_3(aq)$ salt bridge in their laboratory when suddenly the air conditioner began to malfunction and the temperature of the room increased above 25 °C. The redox reaction that they thought would occur was $Fe(s) + CuSO_4(aq) \rightarrow FeSO_4(aq) + Cu(s)$. However, the reverse reaction occurred, despite the galvanic cell being set up under standard pressure and concentration.

a. Suggest a reason for this inconsistency between the reaction predicted by the electrochemical series and Moussa's observations. 1 MARK

b. Over time, Moussa noticed that the voltage was changing, even though they had not disturbed the galvanic cell. Suggest a reason for this. 2 MARKS

Key science skills

Question 16 🌶🌶🌶 (11 MARKS)

Pierre intends to construct their own electrochemical series under certain non-standard conditions based on experimental results. They achieve this by connecting six half-cells to the Cu^{2+}/Cu half-cell and measuring the potential difference between the anode and the cathode. Observations are recorded after the cell is allowed to run for 25 minutes.

a. What two variables must Pierre control in order to collect valid results? Assume that no gaseous reactants are required in any half-cells used. 2 MARKS

The student obtains the following results:

Half-cell connected to Cu^{2+}/Cu half-cell	Voltage measured between electrodes (V)	Observations
Fe^{2+}/Fe	+0.80	• Iron electrode appears thin and pitted • Crystals have formed on the copper electrode • Solution in the Cu^{2+}/Cu half-cell appears less blue
Zn^{2+}/Zn	+1.09	• Zinc electrode appears corroded • Colour of solution in Cu^{2+}/Cu half-cell has become clearer (less blue) • Copper electrode has increased in size
Fe^{3+}/Fe^{2+}	+0.56	• Copper electrode has decreased in size • Cu^{2+} solution has become more blue
Cu^{2+}/Cu	0.00	• No changes observed
MnO_4^-/Mn^{2+} (acidified)	+1.20	• Solution in the MnO_4^-/Mn^{2+} half-cell has become more pink • Size of the copper electrode has decreased • Cu^{2+} solution is a more vibrant blue than when the half-cells were first constructed
Ag^+/Ag	+0.54	• Copper electrode appears small and corroded • Cu^{2+} solution has become more blue • Copper electrode has decreased in size

b. Construct your own electrochemical series (a ranking of these reactions from strongest to weakest oxidising agent strength, as done in the electrochemical series in the VCE Data Book) based on these results, including the half-equations for these reactions. Standard electrode potentials are not required. 6 MARKS

c. How could Pierre increase the validity of their results? Explain. 2 MARKS

d. Why has Pierre not used a $Na^+(aq)/Na(s)$ half-cell in this experiment? 1 MARK

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

Question 17 🌶🌶 (5 MARKS)

Indira wanted to create a galvanic cell by connecting the cadmium standard half cell to the lead standard half cell.

a. Write the equation occurring at the anode. 1 MARK

b. Write the overall redox equation. 1 MARK

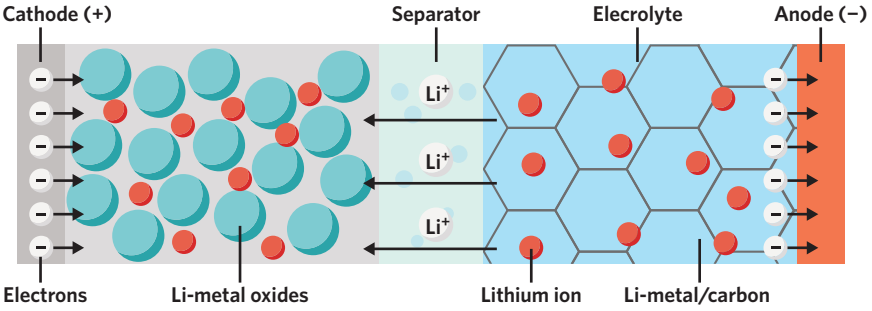
c. Draw a fully labelled diagram of the galvanic cell, labelling all key features including: 4 MARKS

- anode and cathode, including their charges and materials
- direction of electron flow
- direction of ion flow, if a $KNO_3(aq)$ salt bridge is used
- voltage produced by this cell.

FROM LESSONS 3B & 3C

Question 18 (2 MARKS)

A common galvanic cell is the lithium-ion battery. No water is present in this cell, and a metallic mesh allows for the flow of ions between half-cells.



a. Suggest a reason why there is no water present in this galvanic cell. 1 MARK

b. Why is lithium, which is a very strong reducing agent, a popular choice for this galvanic cell? 1 MARK

FROM LESSONS 3B & 3C

Question 19 (3 MARKS)

The table below provides the standard electrode potentials for two reactions that are not included in the electrochemical series in the VCE Data Book. Use the VCE Data Book and the information in the table below to answer this question.

	Standard electrode potential, E^0, in volts
$HOBr(aq) + H^+(aq) + 2e^- \rightleftharpoons Br^-(aq) + H_2O(l)$	+1.33 V
$2HOBr(aq) + 2H^+(aq) + 2e^- \rightleftharpoons Br_2(l) + 2H_2O(l)$	+1.60 V

a. Explain, using standard electrode potentials, why the following reaction between chlorine gas and bromide ions is **not** predicted to occur to any significant extent under standard conditions.

$Cl_2(g) + Br^-(aq) + H_2O(l) \rightleftharpoons 2Cl^-(aq) + H^+(aq) + HOBr(aq)$ 2 MARKS

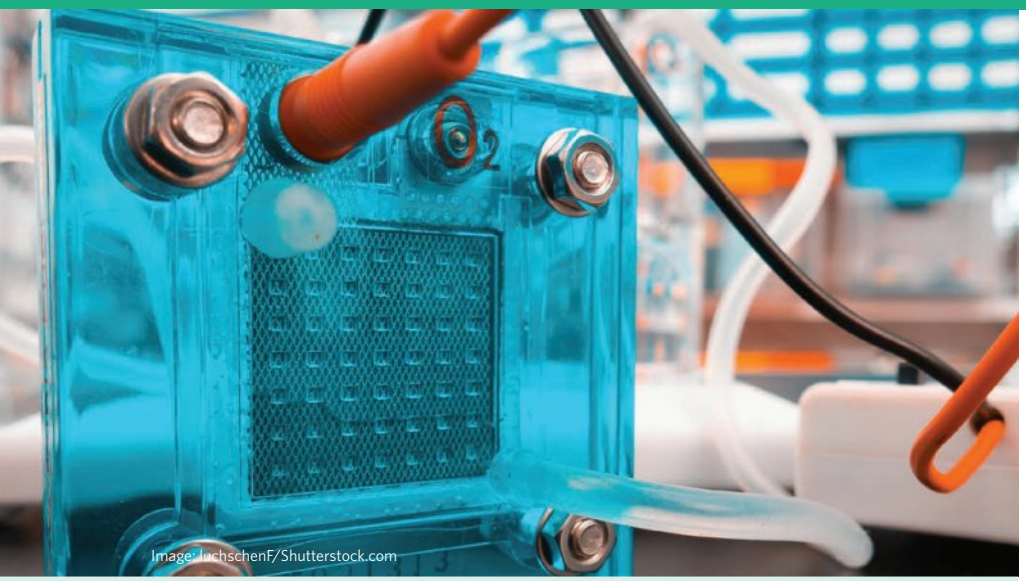
b. Chlorine can be manufactured in the laboratory by reacting concentrated hydrochloric acid with solid manganese(IV) oxide.

$MnO_2(s) + 4HCl(aq) \rightleftharpoons MnCl_2(aq) + 2H_2O(l) + Cl_2(g)$

Write the oxidation half-equation for this reaction. 1 MARK

FROM LESSONS 3B & 3C

3E Fuel cells


Image: IuchschenF/Shutterstock.com

How could fuel cells power transport technology of the future?

In recent years, cars and buses powered by hydrogen **fuel cells** have arrived on the market as a 'zero-emissions' alternative to traditional combustion engines. In this lesson, we will explore the technology of fuel cells.

STUDY DESIGN DOT POINT

- the common design features and general operating principles of fuel cells, including the use of porous electrodes for gaseous reactants to increase cell efficiency (details of specific cells not required)

3A 3B 3C 3D **3E** 3F 3G

3.1.17.1 Structure of fuel cells

3.1.17.2 Function of fuel cells

ESSENTIAL PRIOR KNOWLEDGE

3B Balancing redox equations

3C Primary galvanic cells

See questions 24–25.

KEY TERMS AND DEFINITIONS

Fuel cell electrochemical cell that continuously converts chemical energy into electrical energy via a redox reaction

Porous electrode material with many holes (pores) used in a fuel cell to maximise the ability of gaseous reactants to come into contact with the electrolyte

Structure of fuel cells 3.1.17.1

Although both serve a similar purpose, fuel cells have a number of key features that separate them from other galvanic cells.

What are the key features of fuel cells?

Full cells, like other galvanic cells:

- involve a spontaneous redox reaction
- contain a negative anode (site of oxidation: AnOx) and a positive cathode (site of reduction: RedCat)
- include an electrolyte which allows the passage of ions
- include an external circuit through which electrons flow from the anode to the cathode
- convert chemical energy from a fuel to electrical energy
- have an electrode potential (in V); maximum cell voltage can be calculated under standard conditions
- are generally connected to a 'load' (anything that consumes electrical energy)
- are 'stacked' (multiple cells are connected together) to provide a greater voltage output.

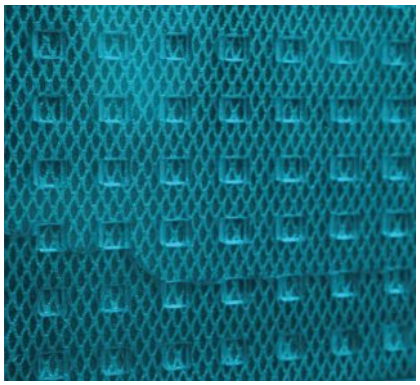


Image: luchschenF/Shutterstock.com

Figure 1 Membrane electrolyte in a fuel cell

However, fuel cells differ from the galvanic cells explored in lesson 3C in the following ways:

- Rather than consuming a set quantity of stored reactants, reactants must be continuously supplied to a fuel cell from an external source in order for electricity to continue to be produced.
- Fuel cells operate in open systems and usually involve gaseous reactants, whereas other galvanic cells usually operate in closed environments and cannot handle gaseous products.
- Membranes are often used as electrolytes in fuel cells. These generally consist of a polymer layer that conducts H^+ ions, known as a proton electrolyte membrane (PEM, shown in figure 1).
- Fuel cells use **porous electrodes**, which allow reactant gases to efficiently diffuse through them and come into contact with the electrolyte. Fuel cell designers carefully choose the size of these pores (the electrodes' 'porosity') to ensure that only the desired molecules can diffuse through (the electrodes' 'selectivity') and hence maximise the cell's overall efficiency. The high surface area created by the many tiny pores also maximises the effectiveness of catalysts (to be discussed further in lesson 4B), increasing reaction rate and hence further improving efficiency.

MISCONCEPTION

'Fuel cells are not galvanic cells.'

Fuel cells are a specific type of galvanic cells (with a number of key defining features).

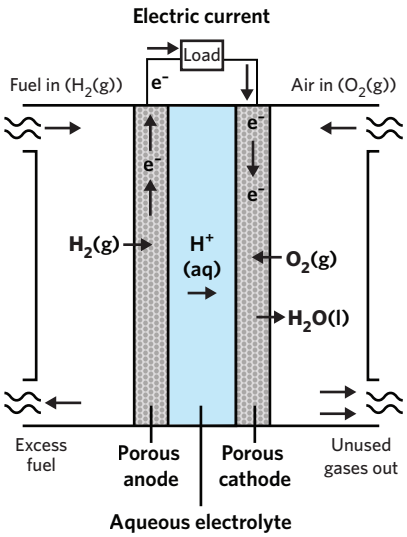


Figure 2 Acidic hydrogen fuel cell

Figure 2 shows a typical example of a fuel cell, using hydrogen as an energy source and an acidic electrolyte. In this setup, hydrogen gas is continuously pumped in as the fuel and oxidised at the anode, while oxygen gas is also continuously supplied as a reactant and reduced at the cathode. The redox half-reactions, overall reaction, and theoretical cell voltage for this fuel cell at standard conditions are as follows (note that real cell voltages are generally lower than theoretical voltages).

Oxidation (anode): $H_2(g) \rightarrow 2H^+(aq) + 2e^-$ $\quad E^0 = 0.00\ V$

Reduction (cathode): $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$ $\quad E^0 = +1.23\ V$

Overall: $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$ $\quad E_{cell} = +1.23\ V$

The overall reaction is always a combustion reaction between a fuel and oxygen; this fuel may be hydrogen or any carbon-containing compound. In this case, the acidic electrolyte, positioned between the two electrodes, provides a source of $H^+(aq)$. However, an alkaline (basic) electrolyte can alternatively be used to provide a source of $OH^-(aq)$, as shown in figure 3.

STRATEGY

To determine the half-reactions or electrode polarities of a fuel cell, remember that oxygen is always reduced at the cathode (positive), and the fuel is always oxidised at the anode (negative).

USEFUL TIP

Fuel cells that use aqueous electrolytes generally operate at temperatures around 80 °C. If higher temperatures were used, the electrolyte would evaporate, terminating the cell's operation. Some fuel cells use non-aqueous electrolytes such as polymer membranes; temperatures above 100 °C are generally used in these cells to maximise reaction rate.

For an alkaline hydrogen fuel cell, the standard half-reactions and overall reaction are as follows.

Oxidation (anode): $H_2(g) + 2OH^-(aq) \rightarrow 2H_2O(l) + 2e^-$ $\quad E^0 = -0.83$ V

Reduction (cathode): $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$ $\quad E^0 = +0.40$ V

Overall: $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$ $\quad E_{cell} = +1.23$ V

USEFUL TIP

When writing fuel cell half-equations, always check whether the electrolyte is acidic (H^+) or alkaline (OH^-), as this affects the balancing.

USEFUL TIP

Although they involve different half-reactions, acidic and alkaline fuel cells that involve the same overall reaction always have the same E^0 value as each other.

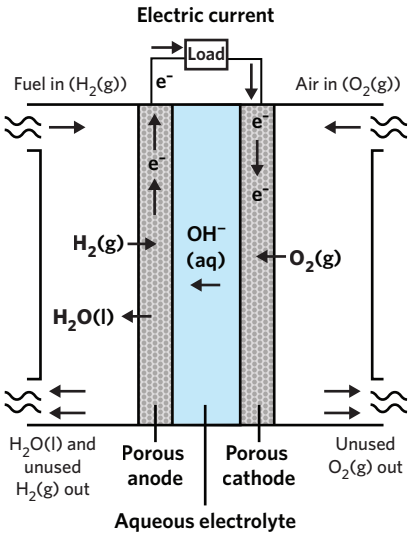
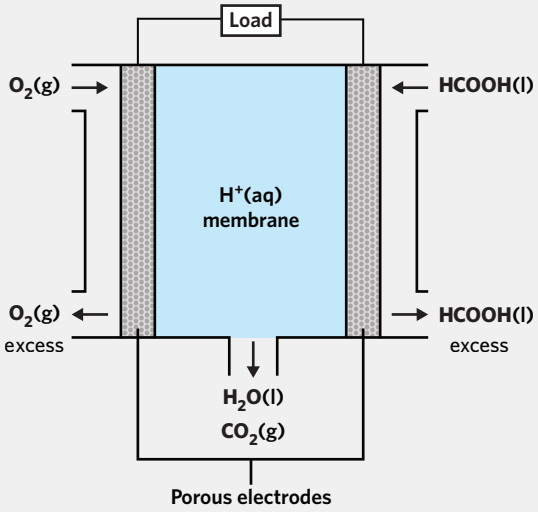


Figure 3 Alkaline hydrogen fuel cell

WORKED EXAMPLE 1

Direct formic acid (methanoic acid) fuel cells (DFAFCs) are fuel cells used in some small electronic devices that are used for medical diagnoses. They use methanoic acid, HCOOH, as a fuel, as well as a membrane electrolyte. An example of a DFAFC is shown.



Write the balanced half-equation (including states) that is occurring at the anode in this fuel cell under standard laboratory conditions.

What information is presented in the question?

A diagram of the fuel cell, including reactants and products.

What is the question asking us to do?

Write a balanced half-equation for the reaction occurring at the anode in this fuel cell.

What strategies do we need in order to answer the question?

1. Identify the reactants and products from the fuel cell diagram.
2. AnOx: oxidation occurs at the anode.
3. Identify the species that is oxidised and the product formed.
4. Identify whether the environment is acidic or alkaline (basic).
5. Balance the oxidation half equation using KOHES.

Answer

At the anode, oxidation occurs.

From the diagram, the reactants are $O_2(g)$ and HCOOH(l), and the products are $H_2O(l)$ and $CO_2(g)$.

$O_2(g)$ is a strong oxidising agent, meaning HCOOH(l) fuel is oxidised to $CO_2(g)$.

The unbalanced equation for the half-reaction occurring at the cathode is

$HCOOH(l) \rightarrow CO_2(g)$

The electrolyte membrane is acidic, so we balance this half-equation using KOHES under acidic conditions (by adding H^+ to balance hydrogen as required), resulting in the balanced half-equation for the anode reaction.

$HCOOH(l) \rightarrow CO_2(g) + 2H^+(aq) + 2e^-$

PROGRESS QUESTIONS

Question 1

Which of the following statements is/are true in a fuel cell?

I. The anode is always positive.

II. Reduction half-reactions occur at the cathode.

III. Electrons travel across the electrolyte.

A. I only **B.** II only

C. I and II only **D.** II and III only

Question 2

All fuel cells

A. are rechargeable and have electrodes that are separated.

B. are galvanic cells and the required reactants are stored in the cells.

C. are rechargeable and the reactants are stored externally and continually supplied.

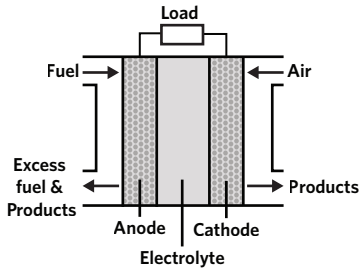
D. convert chemical energy into electrical energy and the reactants are continually supplied.

VCAA (NHT) 2018 exam Multiple choice Q1

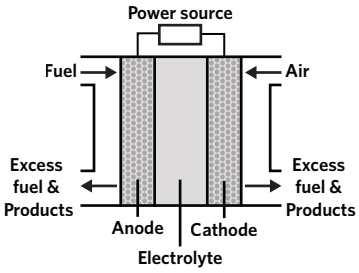
Question 3

Which one of the following diagrams shows the common design features of a fuel cell?

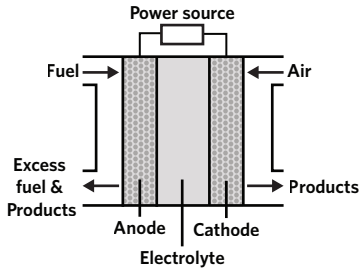
A.



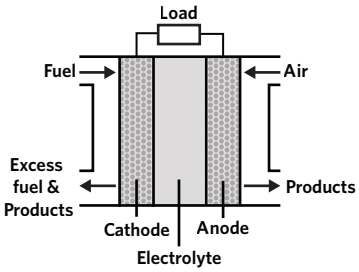
B.



C.



D.



VCAA 2022 exam Multiple choice Q4

Question 4

The overall reaction for an acidic fuel cell is shown below.

$2H_2 + O_2 \rightarrow 2H_2O$

Porous electrodes are often used in acidic fuel cells because they

A. are highly reactive.

B. are cheap to produce and readily available.

C. are more efficient than solid electrodes at moving charges and reactants.

D. provide a surface for the hydrogen and oxygen to directly react together.

VCAA 2018 exam Multiple choice Q12

Function of fuel cells 3.1.17.2

Once considered a 'space-age' alternative, fuel cell-powered products are now available to the public and used in a number of countries around the world.

How can we produce electrical energy from fuel cells?

In a fuel cell, the continuously supplied fuel, a source of chemical energy, is oxidised, producing electrons which pass through the external circuit as electric charge. This charge can be harnessed as electrical energy and used to power appliances, devices such as phones, laptops, cars, trucks, businesses, and homes, among others.[1] Since the electrical output of single fuel cells is insufficient to power large devices, large numbers of fuel cells are 'stacked' together for use in more electrically demanding appliances (figure 4).

The overall reaction occurring in a given fuel cell is equivalent to the combustion reaction of that fuel, though it occurs indirectly. For example, the half-reactions and overall reaction of a direct ethanol fuel cell (DEFC) under acidic conditions are as follows.

MISCONCEPTION

'The protons conducted by a membrane electrolyte are always aqueous and are written as $H^+(aq)$.'

Since the proton is conducted across a solid membrane, it should not have any state symbol (just H^+); just like when an electron is involved in a half-equation, it also does not have a state symbol.

Oxidation (anode): $C_2H_5OH(l) + 3H_2O(l) \rightarrow 12H^+ + 2CO_2(g) + 12e^-$ $\quad E^0 = -0.66$ V

Reduction (cathode): $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l)$ $\quad E^0 = +1.23$ V

Overall: $C_2H_5OH(l) + 3O_2(g) \rightarrow 3H_2O(l) + 2CO_2(g)$ $\quad E_{cell} = +1.89$ V

Compare this overall reaction with the combustion reaction equation of ethanol. Whereas direct combustion converts chemical energy to primarily thermal energy, fuel cells convert chemical energy to electrical energy, with thermal energy produced as a by-product. Table 1 evaluates some of the key factors of fuel cells.[2]

Table 1 Advantages and disadvantages of fuel cells

Advantages	Disadvantages
Lower emissions of harmful sulfur- and nitrogen-containing compounds (compared with direct combustion of fuels)	Storage and safety issues associated with highly explosive hydrogen fuel
Low maintenance and running costs	Expensive to manufacture (particularly porous electrodes)
Quiet	Requires new infrastructure for hydrogen fuel (e.g. refill stations)
No direct CO_2 emissions from hydrogen fuel cells	Hydrogen fuel generally produced via the electrolysis of water: only as environmentally friendly as the electricity used in this process
Much greater efficiency than direct combustion, particularly if thermal energy produced is harnessed for car/home heating	Potentially still not as efficient or convenient as batteries

KEEN TO INVESTIGATE?

[1] **How do hydrogen-powered cars work?**
Search YouTube: I drove 1800 miles in a hydrogen car

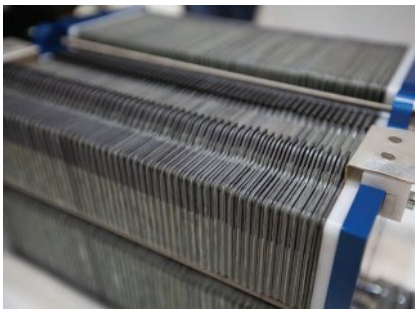


Image: Blake Choquer/Shutterstock.com

Figure 4 Hydrogen fuel cells stacked to power a vehicle engine

KEEN TO INVESTIGATE?

[2] **Why aren't hydrogen fuel cells more widely used?**
Search YouTube: Why hydrogen will not save us

USEFUL TIP

It is not required knowledge to memorise the details of any specific fuel cells; in VCAA exams, specific cell details will be provided. It is hence important to be able to apply the general principles of fuel cells to a wide range of possible cells.

PROGRESS QUESTIONS

Question 5

Which of the following statements regarding fuel cells is **incorrect**?

A. Fuel cells always produce heat as a by-product.

B. Fuel cells are cheap to manufacture, but expensive to maintain.

C. The fuel for fuel cells must be stored externally.

D. High efficiency and low emissions are generally two benefits of fuel cells.

Theory summary

- Fuel cells are a specific type of galvanic cell that:
  - produce electrical energy (and heat as a by-product) from a supplied fuel via a redox reaction
  - require a continuous supply of reactants from an external source
  - use porous electrodes to maximise efficiency of diffusion of gaseous reactants and to maximise the ability of catalysts
  - are used to power small electronic devices, vehicles, and more.
- To calculate theoretical (maximum) cell voltage for fuel cells:
  - $E_{cell} = E^0$ of reduction reaction (most positive) $- E^0$ of oxidation reaction (least positive)

3E Questions

Mild Medium Spicy

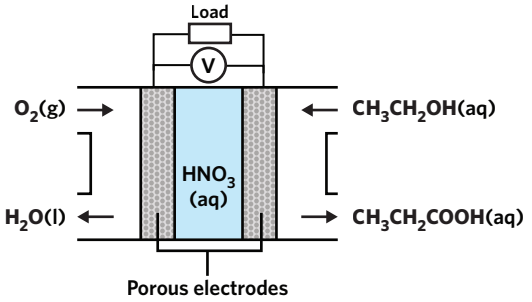
Deconstructed

Use the following information to answer questions 6–8.

A goal for many researchers is to develop fuel cells that do not produce CO_2. One such example is a cell that oxidises ethanol fuel to ethanoic acid. The following electrochemical series entry is provided.

$CH_3COOH(aq) + 4H^+(aq) + 4e^- \rightarrow CH_3CH_2OH(aq) + H_2O(l) \quad E^0 = +0.06\ V$

A diagram of this cell is also shown.



Question 6 (1 MARK)

The formula for the theoretical voltage of a fuel cell can be expressed as

A. $E_{cell} = E^0$ of reduction reaction $+ E^0$ of oxidation reaction

B. $E_{cell} = E^0$ of oxidation reaction $- E^0$ of reduction reaction

C. $E_{cell} = E^0$ of reduction reaction $- E^0$ of oxidation reaction

D. $E_{cell} = -E^0$ of oxidation reaction $- E^0$ of reduction reaction

Question 7 (1 MARK)

The reduction half-equation and corresponding E^0 value for this cell are

A. $H_2O_2(aq) + 2H^+(aq) + 2e^- \rightarrow 2H_2O(l) \quad E^0 = +1.77\ V$

B. $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l) \quad E^0 = +1.23\ V$

C. $O_2(g) + 2H^+(aq) + 2e^- \rightarrow H_2O_2(aq) \quad E^0 = +0.68\ V$

D. $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq) \quad E^0 = +0.40\ V$

Question 8 (1 MARK)

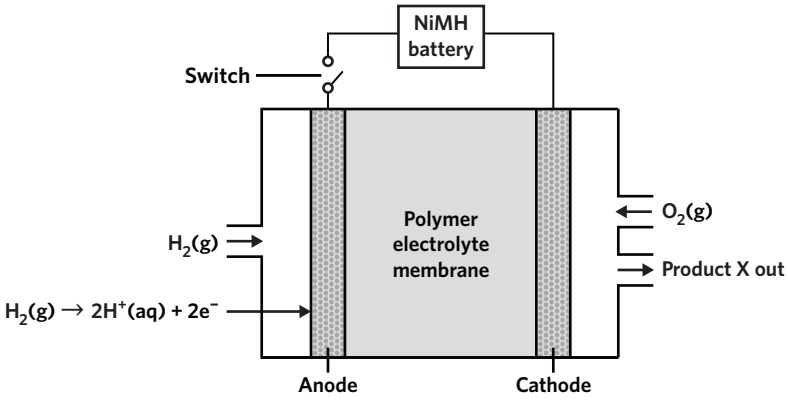
The theoretical voltage of this cell is

A. +1.17 V **B.** +1.29 V **C.** −1.17 V **D.** −1.29 V

Exam-style

Question 9 (6 MARKS)

A car manufacturer is planning to sell hybrid cars powered by a type of hydrogen fuel cell, which produces electrical energy to charge a nickel metal hydride, NiMH, battery. A representation of the hydrogen fuel cell is given below.



The overall cell reaction is: $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

a. Identify the product X. 1 MARK

b. Write an equation for the half-reaction that occurs at the cathode when the switch is closed. 1 MARK

c. Identify one advantage and one disadvantage of using this fuel cell instead of a petrol engine to power the car.

i. Advantage 1 MARK

ii. Disadvantage 1 MARK

d. The use of porous electrodes is necessary in fuel cells to ensure that gaseous reactants efficiently come into contact with the electrolyte. Besides this, identify one advantage and one disadvantage of using porous electrodes.

i. Advantage 1 MARK

ii. Disadvantage 1 MARK

Adapted from VCAA 2015 exam Short answer Q10a

Question 10 (7 MARKS)

A methanol fuel cell is an experimental type of fuel cell currently being researched as a potential source of energy for electronic devices and small vehicles. The half-reactions occurring in a given methanol fuel cell (using an aqueous electrolyte) are as follows:

Oxidation: $CH_3OH(l) + H_2O(l) \rightarrow CO_2(g) + 6H^+(aq) + 6e^-$ $\quad E^0 = -0.39$ V

Reduction: $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$ $\quad E^0 = +1.23$ V

a. What is the overall reaction occurring in this fuel cell? 1 MARK

b. Draw a design for this fuel cell, including: 4 MARKS

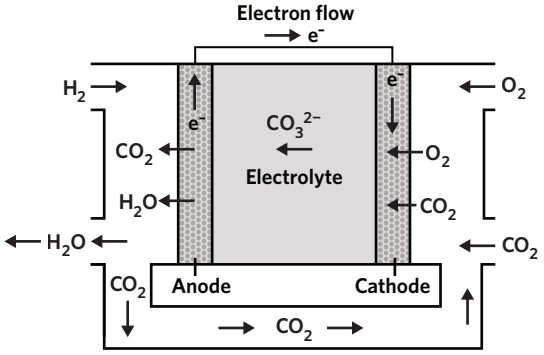
- species entering/exiting the cell
- anode and cathode
- electrode polarities and direction of electron flow
- a possible electrolyte and the direction of ion flow.

c. What is the theoretical voltage produced by this cell at SLC? 1 MARK

d. A vehicle manufacturer suggests running the fuel cell at 200 °C to speed up the fuel cell's operation. Explain why this would not work for this fuel cell. 1 MARK

Use the following information to answer Questions 11–12.

Scientists have developed a new type of hydrogen fuel cell for use on a large scale in factories and manufacturing plants, as shown in the diagram below. The fuel cell operates at 600 °C.



Question 11 (1 MARK)

Which one of the following statements is accurate for this type of hydrogen fuel cell?

A. Heat is a by-product of this hydrogen fuel cell.

B. O_2 is oxidised to produce CO_2.

C. The enthalpy of the reactants is less than the enthalpy of the products.

D. CO_2 is released into the environment.

VCAA (NHT) 2021 exam Multiple choice Q29

Question 12 (1 MARK)

The equation for the half-cell reaction occurring at the positive electrode in the diagram above is

A. $2CO_2 + 4H_2O + 4e^- \rightarrow O_2 + 2CO_3^{2-} + 8H^+$

B. $H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$

C. $H_2O + CO_2 + 2e^- \rightarrow CO_3^{2-} + H_2$

D. $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$

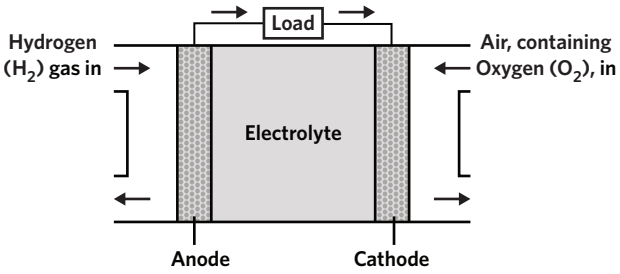
VCAA (NHT) 2021 exam Multiple choice Q28

Key science skills

Question 13 (8 MARKS)

Submarines operate both on the surface and underwater. When operating underwater, the submarine acts as a closed system, where there is no interaction with the atmosphere. Most types of submarines use both batteries and diesel engines to provide their energy requirements. A new type of submarine uses proton electrolyte membrane (PEM) fuel cells and diesel engines.

a. A diagram of a PEM fuel cell is shown.



i. State the function of the electrolyte in a fuel cell. 1 MARK

ii. Write the balanced overall redox reaction (including states) that occurs in this PEM fuel cell. 1 MARK

iii. Hydrogen gas presents a risk of explosion and is generally stored under high pressure. Give **two** safety measures that should be taken for the safe storage of hydrogen, H_2, gas on a submarine. 2 MARKS

b. When a submarine is underwater, its engine or fuel cell is in use. When a submarine is travelling on the surface, it interacts with the sun and the atmosphere.

i. State two advantages of using a PEM fuel cell compared to a diesel engine when a submarine is underwater. 2 MARKS

ii. Most submarines replenish H_2 gas for their fuel cells when travelling on the surface. Explain how this H_2 gas could be generated. 2 MARKS

Adapted from VCAA 2017 exam Short answer Q6

FROM LESSONS 12A & 12B

Questions from multiple lessons

Question 14 (1 MARK)

Consider the following statements about galvanic cells and fuel cells.

Statement number	Statement
1	The overall reaction is exothermic.
2	Electrons are consumed at the negative electrode.
3	Both the reducing agent and the oxidising agent are stored in each half-cell.
4	The electrodes are in contact with the reactants and the electrolyte.
5	The production of electricity requires the electrodes to be replaced regularly.

Which of the following sets of statements is correct for **both** galvanic cells and fuel cells?

A. Statements 2 and 3

B. Statements 1 and 4

C. Statements 2, 4, and 5

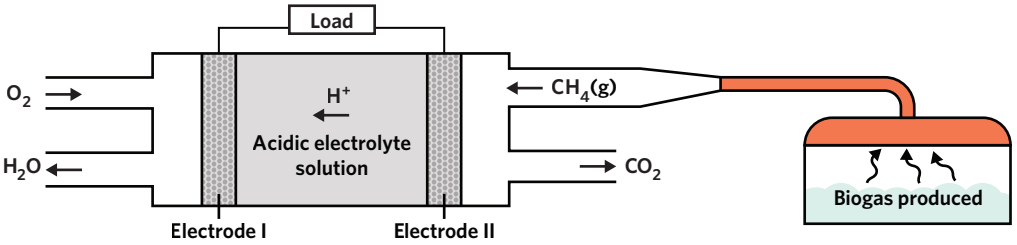
D. Statements 1, 3, and 5

VCAA 2019 exam Multiple choice Q8

FROM LESSON 3C

Question 15 (13 MARKS)

Biogas from organic waste presents a possible major source of energy, and scientists have developed a fuel cell designed to harness methane from biogas to produce electrical energy. A design for this fuel cell is shown.



a. What species is oxidised in this fuel cell? 1 MARK

b. Identify the respective polarities of electrodes I and II. 1 MARK

c. Give the balanced half-equation for the oxidation reaction occurring in this fuel cell. 1 MARK

d. Give the balanced overall equation (including states) for the redox reaction occurring in this fuel cell. 2 MARKS

e. If an alkaline electrolyte were instead used, give the balanced overall equation that would occur in this fuel cell. 1 MARK

f. If the electrodes were not porous, explain what would happen in this cell. 2 MARKS

g. If 1.00 kg of methane is supplied as fuel to this fuel cell with excess oxygen, calculate the total mass (in kg) of greenhouse gases produced. 3 MARKS

h. Explain two environmental advantages of this fuel cell. 2 MARKS

FROM LESSONS 1B & 2A

3F Faraday's Laws in galvanic and fuel cells

STUDY DESIGN DOT POINT

- the application of Faraday's Laws and stoichiometry to determine the quantity of galvanic or fuel cell reactant and product, and the current or time required to either use a particular quantity of reactant or produce a particular quantity of product

3A 3B 3C 3D 3E **3F** 3G

3.1.18.1 Faraday's Laws in galvanic cells

3.1.18.2 Faraday's Laws in fuel cells

ESSENTIAL PRIOR KNOWLEDGE

- Avogadro constant

2A Mass/volume-based stoichiometry

3B Stoichiometric ratios in balanced half-equations

See questions 26–28.

MISCONCEPTION

'Faraday's Laws of electrolysis only apply to electrolysis.'

From 2024 onwards, the application of Faraday's Laws to galvanic and fuel cells (as well as electrolysis) is examinable in VCE chemistry.

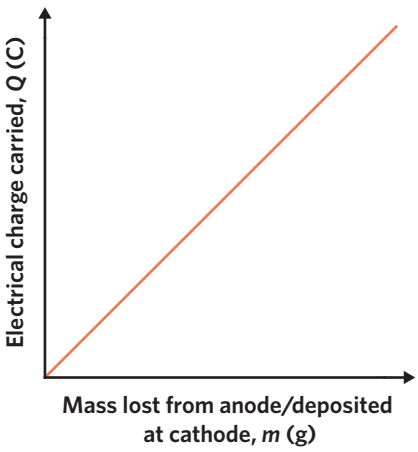


Figure 1 Relationship between change in mass and charge carried in galvanic cells


Image: Happy Whale/Shutterstock.com

How long does a space station's power source last?

Space stations need energy sources able to provide enough power for long periods without external electricity. In this lesson, we will investigate how quantities such as time of operation, current, **electric charge**, reactant amounts, and product amounts can be calculated for galvanic and fuel cells, using stoichiometry and Faraday's Laws.

KEY TERMS AND DEFINITIONS

Coulomb unit of electric charge (equal to the quantity of charge carried by a current of 1 ampere in 1 second)

Electric charge property of matter carried by current and measured in coulombs, where the charge on a single electron is -1.60×10^{-19} coulombs

Faraday constant (*F*) charge on one mole of charged particles, equal to 96 500 coulombs per mole

Faraday's Laws in galvanic cells 3.1.18.1

In 1833, the English scientist Michael Faraday discovered two major quantitative relationships in electrochemistry, which have become known as Faraday's Laws of electrolysis (a concept that will be discussed in lesson 6D). However, Faraday's Laws are equally applicable to galvanic and fuel cells.

What are Faraday's Laws?

Faraday's First Law

In the context of galvanic cells, Faraday's First Law states that the quantity of electric charge (i.e. electricity: Q, in **coulombs**) carried by a given galvanic cell is directly proportional to the mass (m, in grams) lost from the anode or gained at the cathode. This relationship can be written as $Q \propto m$, where the symbol '$\propto$' means 'is directly proportional to', and can be graphically represented as shown in figure 1. For example, if the mass of the anode were doubled, the theoretical quantity of charge carried by this galvanic cell would also double.

Faraday's Second Law

In the context of galvanic cells, Faraday's Second Law states that for a given starting amount of anode, the number of moles of electrons produced by a galvanic cell ($n(e^-)$) is directly proportional to the coefficient of electrons in the balanced oxidation half-equation (x, a positive whole number). This is demonstrated in table 1. This relationship is also evident from the stoichiometric ratio of the oxidation half-equation.

Table 1 Examples of Faraday's Second Law applied to galvanic cells

Starting anode amount and material	Oxidation half-equation	x (coefficient of e^-)	Number of moles of electrons generated
1 mol of silver atoms	$Ag(s) \rightarrow Ag^+(aq) + e^-$	1	1
1 mol of zinc atoms	$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$	2	2
1 mol of aluminium atoms	$Al(s) \rightarrow Al^{3+}(aq) + 3e^-$	3	3

How can we calculate quantities in galvanic cells?

On their own, Faraday's Laws are not immediately useful. However, the formulas derived from them are vital for calculating quantities in galvanic cells.

A relationship key to these calculations is $Q = I \times t$, where Q is the quantity of electrical charge in coulombs (C), I is the current in amperes (A), and t is the time in seconds (s). For example, if a galvanic cell produces a current of 1.2 A for 60 seconds, $1.2 \times 60 = 72$ C of charge is carried.

Another key component of these calculations is the **Faraday constant (F)**, which represents the charge on one mole of electrons. This can be calculated as the absolute value of the product of the Avogadro constant (the number of electrons in one mole, $N_A = 6.02 \times 10^{23}$ mol^{-1}) and elementary charge (the charge on one electron, $e = -1.60 \times 10^{-19}$ C), both of which values are given in the VCE Data Book.[1] The Faraday constant, F, is given as 96 500 C mol^{-1} in the VCE Data Book.

USEFUL TIP

Recall from VCE chemistry Unit 1 that the number of moles of particles (e.g. electrons) is equal to the number of particles (N) divided by the Avogadro constant (N_A): $n = \frac{N}{N_A}$.

The Faraday constant combines with Faraday's Laws to give the formula $n(e^-) = \frac{Q}{F}$, where $n(e^-)$ is the number of moles of electrons passing through the external circuit of the galvanic cell (in mol), Q is the quantity of charge carried (in coulombs, C), and $F = 96\,500$ C mol^{-1} is the Faraday constant.

This formula can be rearranged and combined with the formula $Q = It$, as well as the stoichiometric methods explored in lesson 2A, to calculate:

- the required anode mass
- the amount or mass of product produced at the cathode
- the quantity of charge generated
- the current passed
- or the duration of operation of a galvanic cell.

USEFUL TIP

The formula $Q = It$ is provided in the VCE Data Book (not to be confused with the formula $q = VIt$). The unit of current, A, is equivalent to C s^{-1} (coulombs per second), hence the units cancel out correctly.

KEEN TO INVESTIGATE?

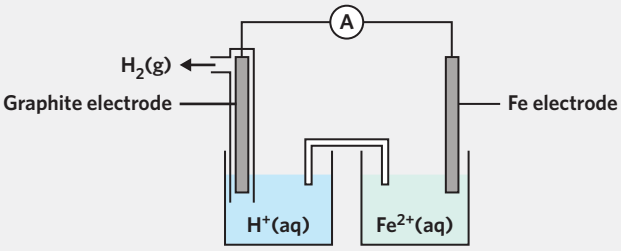
1 **How was the charge on one electron determined for the first time?**
Search: Millikan's oil drop experiment

USEFUL TIP

One 'faraday' of charge is sometimes used to denote the amount of charge equivalent to that of one mole of electrons: 96 500 C mol^{-1}.

WORKED EXAMPLE 1

A student sets up a galvanic cell with an ammeter as shown.



The iron, Fe, anode initially weighed 50.00 g. After the cell was connected for 15 minutes, the iron anode was re-weighed as 49.72 g. What was the average ammeter reading (in amps) for the time that the cell was connected?

What information is presented in the question?

A labelled diagram of the galvanic cell.

The iron electrode is the anode.

The anode decreased in mass from 50.00 g to 49.72 g.

The cell operated for 15 minutes.

What is the question asking us to do?

Calculate the current generated by this cell during its operation.

What strategies do we need in order to answer the question?

1. Determine the oxidation half-equation.
2. Calculate the change in mass of the anode.
3. Calculate the number of moles of anode consumed using $n = \frac{m}{M}$.
4. Calculate the number of moles of electrons using stoichiometric ratios.
5. Calculate the total charge carried using $n(e^-) = \frac{Q}{F}$.
6. Convert the time of operation to seconds.
7. Calculate the current using $Q = It$.

Answer

The iron anode oxidises according to the half-equation

$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$

$m(\text{Fe consumed}) = m(\text{Fe initial}) - m(\text{Fe final})$

$m(\text{Fe consumed}) = 50.00\text{ g} - 49.72\text{ g}$

$m(\text{Fe consumed}) = 0.28\text{ g}$

$n(\text{Fe}) = \frac{m}{M}$

$n(\text{Fe}) = \frac{0.28\text{ g}}{55.8\text{ g mol}^{-1}}$

$n(\text{Fe}) = 0.00502\text{ mol}$

$n(e^-) : n(\text{Fe})$

$2 : 1$

$n(e^-) = 2 \times n(\text{Fe})$

$n(e^-) = 2 \times 0.00502\text{ mol}$

$n(e^-) = 0.01004\text{ mol}$

$Q = n(e^-) \times F$

$Q = 0.01004\text{ mol} \times 96\,500\text{ C mol}^{-1}$

$Q = 968.5\text{ C}$

$t = 15\text{ minutes}$

$t = 15 \times 60\text{ s}$

$t = 900\text{ s}$

$I = \frac{Q}{t}$

$I = \frac{968.5\text{ C}}{900\text{ s}}$

$I = 1.08\text{ A}$

Therefore, the average ammeter reading was 1.1 A (2 sig. figs).

USEFUL TIP

For Faraday's Laws calculation questions in VCAA exams, one mark is often allocated to writing the correct half-equation for determining stoichiometric ratios.

PROGRESS QUESTIONS

Question 1

A galvanic cell is set up with a copper anode, and after the anode has decreased in mass by 25 g, the cell has carried 3.8×10^4 C of charge. How much charge is expected to have been carried once the anode has decreased in mass by 75 g? Assume all other reactant species are in excess.

A. 1.1×10^4 C

B. 1.3×10^4 C

C. 3.8×10^4 C

D. 1.1×10^5 C

Continues →

Question 2

A galvanic cell produces a current of 0.50 A for a total duration of 180 seconds. What is the quantity of charge generated by this cell?

A. 1.5 C

B. 54 C

C. 90 C

D. This cannot be determined from the information given.

Question 3

Assuming that all other reactant species are in excess, which of the following anodes in a galvanic cell will result in the greatest amount of electrons generated, once the anode has been completely used up?

A. 1 mol aluminium anode

B. 1 mol cobalt anode

C. 2 mol nickel anode

D. 3 mol silver anode

Question 4

6.85×10^4 C of charge is carried by a galvanic cell with nickel and aluminium electrodes. How many moles of electrons pass through the external circuit of this galvanic cell?

A. 0.710 mol

B. 1.41 mol

C. 1.42 mol

D. 2.13 mol

Faraday's Laws in fuel cells 3.1.18.2

Faraday's Laws can similarly be applied to fuel cell calculations.

How can we calculate quantities in fuel cells?

Like with other galvanic cells, stoichiometry and Faraday's laws can be used to calculate various quantities in fuel cells. These quantities include, but are not limited to:

- the length of time for which a fuel cell can run before its fuel supply is exhausted
- the mass or volume of fuel required to produce a given quantity of electricity (charge)
- and the mass or volume of greenhouse gases produced by a fuel cell over a given duration of time.

The major difference between galvanic and fuel cell calculations is that fuel cells much more commonly involve gaseous reactants and products. As a result, volumes of gaseous reactants and products only need to be calculated under standard laboratory conditions (SLC), as explored in lesson 2A, using the formula $V = n \times V_m$ (a rearrangement of the version presented in the VCE Data Book).

Figure 2 summarises the Faraday's Laws calculations involved in any electrochemical cell: galvanic, fuel, or electrolytic (explored in lesson 6E).

STRATEGY

Although most formulas are provided in the VCE Data Book, only one version of each is generally given. It may be helpful to write and continually update your own formula sheet over the course of VCE chemistry Units 3 & 4 as a revision technique.

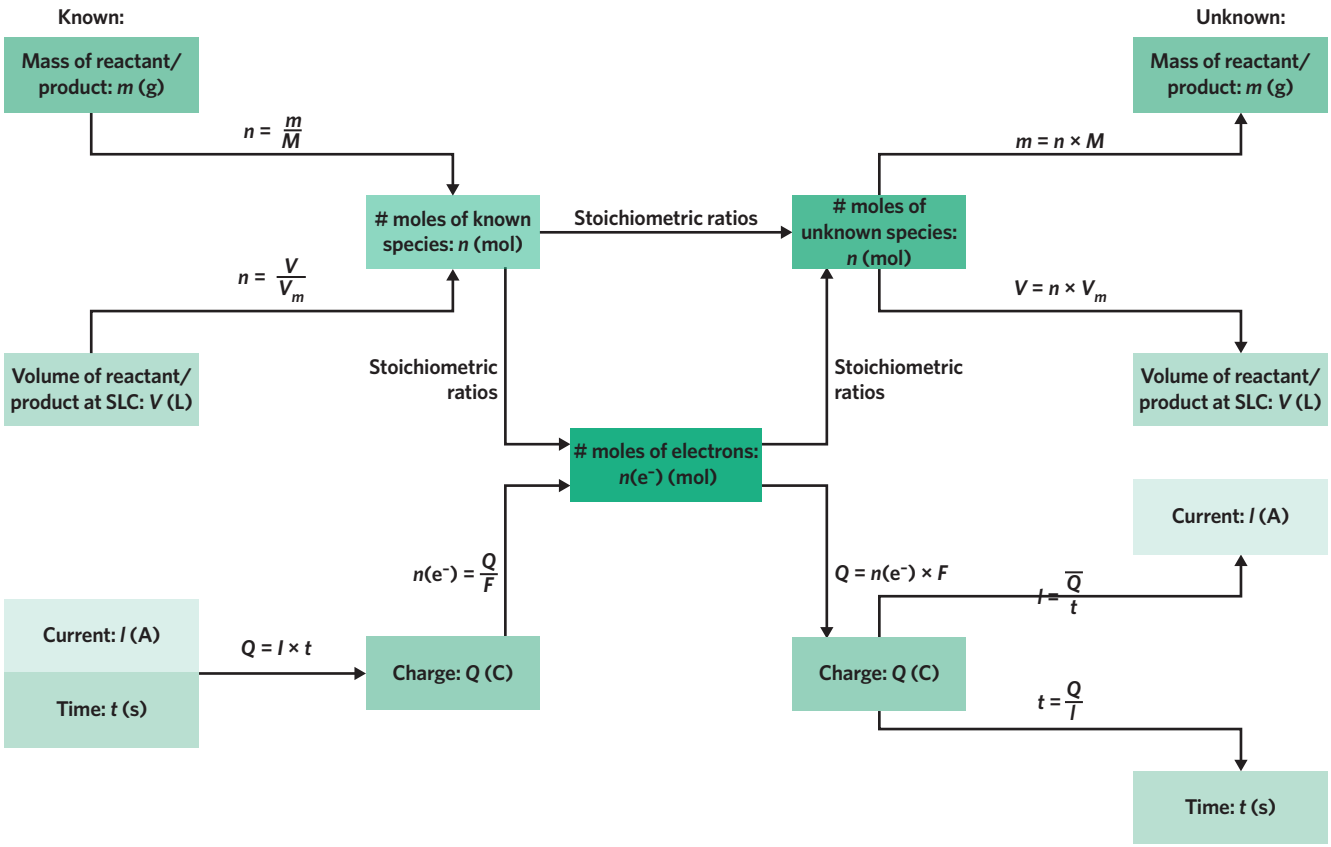


Figure 2 Flowchart of methods for Faraday's Laws calculations

WORKED EXAMPLE 2

An experimental fuel cell uses ethane gas as fuel, and involves the following half-equations:

Anode half-reaction: $C_2H_6(g) + 4H_2O(l) \rightarrow 14H^+(aq) + 2CO_2(g) + 14e^-$

Cathode half-reaction: $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$

What volume (in L) of ethane gas is required to produce a current of 12 A for 2.00 hours using this fuel cell under standard laboratory conditions (SLC)?

What information is presented in the question?

The half-equations occurring in the fuel cell.

The fuel cell generates a current of 12 A.

The fuel cell operates for 2.00 hours.

What is the question asking us to do?

Calculate the volume of ethane gas required to produce a current of 12 A for 2.00 hours.

What strategies do we need in order to answer the question?

1. Convert the time of operation to seconds.
2. Calculate the charge carried using $Q = It$.
3. Calculate the number of moles of electrons using $n(e^-) = \frac{Q}{F}$.
4. Calculate the number of moles of ethane gas using stoichiometric ratios.
5. Calculate the volume of ethane gas consumed at SLC using $V = n \times V_m$.

Answer

$t = 2.00$ hours

$t = 2.00 \times 60 \times 60$ s

$t = 7200$ s

$Q = It$

$Q = 12\text{ A} \times 7200\text{ s}$

$Q = 86\,400$ C

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{86\,400\text{ C}}{96\,500\text{ C mol}^{-1}}$

$n(e^-) = 0.8953$ mol

$n(C_2H_6) : n(e^-)$

$1 : 14$

$n(C_2H_6) = \frac{1}{14} \times n(e^-)$

$n(C_2H_6) = \frac{1}{14} \times 0.8953$ mol

$n(C_2H_6) = 0.06395$ mol

$V(C_2H_6) = n \times V_m$

$V(C_2H_6) = 0.06395\text{ mol} \times 24.8\text{ L mol}^{-1}$

$V(C_2H_6) = 1.6$ L (2 sig. figs)

PROGRESS QUESTIONS

Use the following information to answer questions 5–6.

In an acidic hydrogen fuel cell, operating at SLC, hydrogen gas is oxidised according to the following half-equation.

$H_2(g) \rightarrow 2H^+(aq) + 2e^-$

Oxygen gas is also reduced in this fuel cell according to the following half- equation.

$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$

In a given instance, 3.00 mol of electrons passed through the external circuit.

Question 5

What volume of hydrogen gas was supplied to the fuel cell in this instance?

A. 1.50 L **B.** 37.2 L **C.** 6.00 L **D.** 74.4 L

Question 6

What mass of water was produced in this instance?

A. 18.0 g **B.** 27.0 g **C.** 36.0 g **D.** 54.0 g

Question 7

A small, fuel cell-powered electronic device contains enough fuel to carry a total charge of 7200 C, and it produces a current of 0.330 A when the device is switched on. For how long can the device be switched on?

A. 2.38×10^3 s

B. 2.18×10^4 s

C. 3.18×10^5 s

D. 1.48×10^6 s

Theory summary

- Faraday's Laws state that:
  - The amount of charge carried by a galvanic/fuel cell is directly proportional to the mass of anode lost/fuel used.
  - The number of moles of electrons produced by a galvanic or fuel cell is directly proportional to the coefficient of electrons in the balanced oxidation half-equation.
- The amount of charge carried by a galvanic or fuel cell, Q (in C), can be calculated using the formula $Q = It$, where I (in A) is the current and t (in seconds) is the time for which the cell operates.
- The Faraday constant, $F = 96\,500$ C mol^{-1}, is the charge on one mole of electrons.
- The number of moles of electrons, $n(e^-)$ (in mol), passing through the external circuit of a galvanic or fuel cell can be calculated using the formula $n(e^-) = \frac{Q}{F}$, where Q (in C) is charge carried and F is the Faraday constant.
- Stoichiometry can be combined with these formulas to calculate masses or volumes of products or reactants in galvanic or fuel cells.

3F Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 8–10.

An Australian company in 2009 developed a solid oxide fuel cell (SOFC) that operates at 60% efficiency using very high temperatures (around 800 °C). The half-reactions and overall reaction occurring in this SOFC, which uses methane gas as fuel, are as follows.

Anode half-reaction: $CH_4(g) + 2H_2O(l) \rightarrow 8H^+ + CO_2(g) + 8e^-$

Cathode half-reaction: $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l)$

Overall reaction: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

Question 8 (1 MARK)

What is the ratio of the number of moles of methane to the number of moles of electrons?

A. 1 : 4

B. 1 : 8

C. 4 : 1

D. 8 : 1

Question 9 (1 MARK)

To generate the same quantity of charge, a 60% efficient fuel cell uses

A. 0.60 times the amount of fuel required for an 100% efficient fuel cell.

B. $\frac{1}{0.60}$ times the amount of fuel required for an 100% efficient fuel cell.

C. the same amount of fuel as an 100% efficient fuel cell (as efficiency does not affect charge).

D. either 0.60 or $\frac{1}{0.60}$ times the amount of fuel required for an 100% efficient cell (depending on the fuel cell).

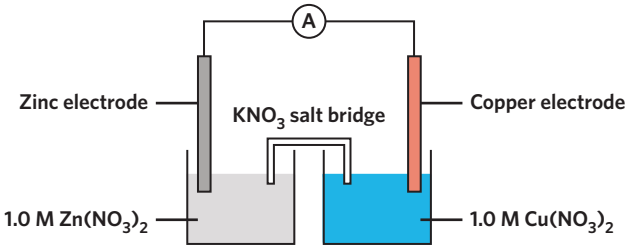
Question 10 (3 MARKS)

At 60% efficiency, what volume of methane gas is required for 5.00×10^6 C of charge to be carried by this fuel cell?

Exam-style

Question 11 (5 MARKS)

Tori sets up the following galvanic cell.



The cell produced a current of 2.30 A for a total of 180 seconds.

a. How much charge was carried during the total operation of this galvanic cell? 1 MARK

b. How many moles of electrons passed through the external circuit? 1 MARK

c. How would your answer to part **b** change if Tori had used a silver electrode instead of a copper electrode for their experiment? Justify your answer using redox half-equations and one of Faraday's Laws. 3 MARKS

Question 12 (1 MARK)

A hydrogen-oxygen fuel cell uses 1.00×10^{-5} mol of hydrogen gas per second of operation.
What is the current produced by this cell?

A. 0.483 A

B. 0.965 A

C. 1.93 A

D. 3.86 A

VCAA 2014 exam Multiple choice Q29

Question 13 (1 MARK)

How many electrons constitute 1.00 coulombs of charge?

A. 6.24×10^{18}

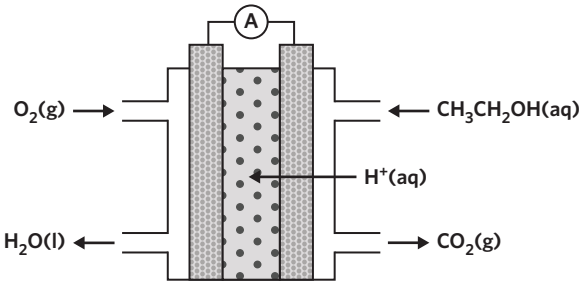
B. 1.60×10^{19}

C. 6.02×10^{23}

D. 5.81×10^{28}

Question 14 (5 MARKS)

Currently, direct ethanol fuel cells (DEFCs) operate at an efficiency of 30%. A diagram of a DEFC using a membrane electrolyte is shown.



The unbalanced oxidation half-equation for a DEFC is $CH_3CH_2OH \rightarrow CO_2$.

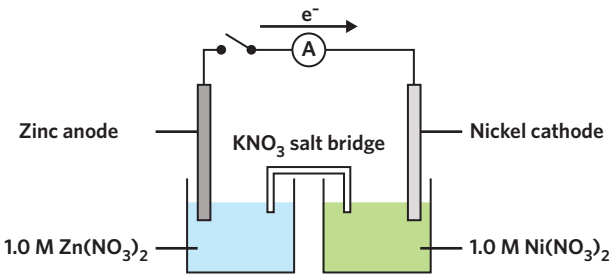
a. Write the balanced oxidation half-equation (not including states) occurring in this DEFC. 1 MARK

b. A communication device on the International Space Station requires a current of approximately 1.04 A to operate. If 0.100 mol of ethanol is supplied as fuel, for how long (in hours) can this fuel cell produce a current of 1.04 A if it operates at 30% efficiency? 4 MARKS

Key science skills

Question 15 (7 MARKS)

A student wishes to devise an experiment to verify the value of the Faraday constant using a galvanic cell.
A diagram of this cell is shown.



a. Using this apparatus, suggest a method the student could use (including any formulas) to verify the value of the Faraday constant. 5 MARKS

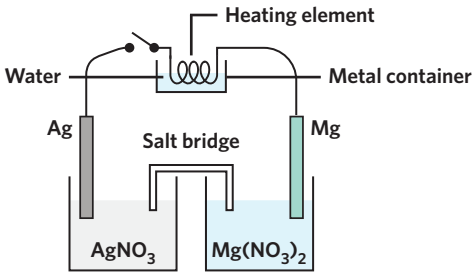
b. Assuming all calculations are performed correctly, give two possible reasons for any potential disparity between the theoretical value of *F* and the experimental value determined by the student. 2 MARKS

FROM LESSONS 12B & 12D

Questions from multiple lessons

Question 16 (9 MARKS)

A student wants to use the energy produced from a galvanic cell to heat water in a container.



a. The student begins by setting up the cell as shown and closing the switch.

i. What half-equation is occurring at each electrode in this cell? 2 MARKS

ii. What is the theoretical voltage (in V) produced by this cell? 1 MARK

b. After the cell is connected for 300 seconds, the student obtains the following results.

	Initial mass (g)	Final mass (g)
Silver electrode	3.700	4.589
Magnesium electrode	0.440	0.340

Assuming 100% efficiency:

i. What is the charge (in C) carried by this cell? 3 MARKS

ii. What is the current (in A) produced by this cell? 1 MARK

c. The mass of water in the metal container is found to be 50.0 g.

i. Over the course of this experiment, what is the theoretical amount of energy (in J) produced by this cell? 1 MARK

ii. What is the expected increase in temperature of the water over the course of this experiment? Assume all energy produced by the cell is transferred to the water. 1 MARK

FROM LESSONS 2B, 3B & 3D

Question 17 (8 MARKS)

Recently, cars powered by acidic hydrogen fuel cells have been made available for the public to purchase. After getting his driver's licence, Arman wants to compare the relative efficiencies of internal combustion engines and fuel cells.

a. Arman finds that an internal combustion engine produces 27.7 MJ of energy (1 MJ = 10^6 J) when 1.65 kg of octane is combusted within it. Calculate the percentage efficiency of this internal combustion engine, assuming standard laboratory conditions. 2 MARKS

b. The hydrogen fuel cell was found to carry 9.50×10^3 C of charge when 2.03 L of hydrogen gas was consumed, and the half-equation occurring at the anode in this fuel cell is $H_2 \rightarrow 2H^+ + 2e^-$. Calculate the percentage efficiency of the hydrogen fuel cell, assuming the conditions are SLC. 4 MARKS

c. For the use of fuel cells in motor vehicles, identify one:

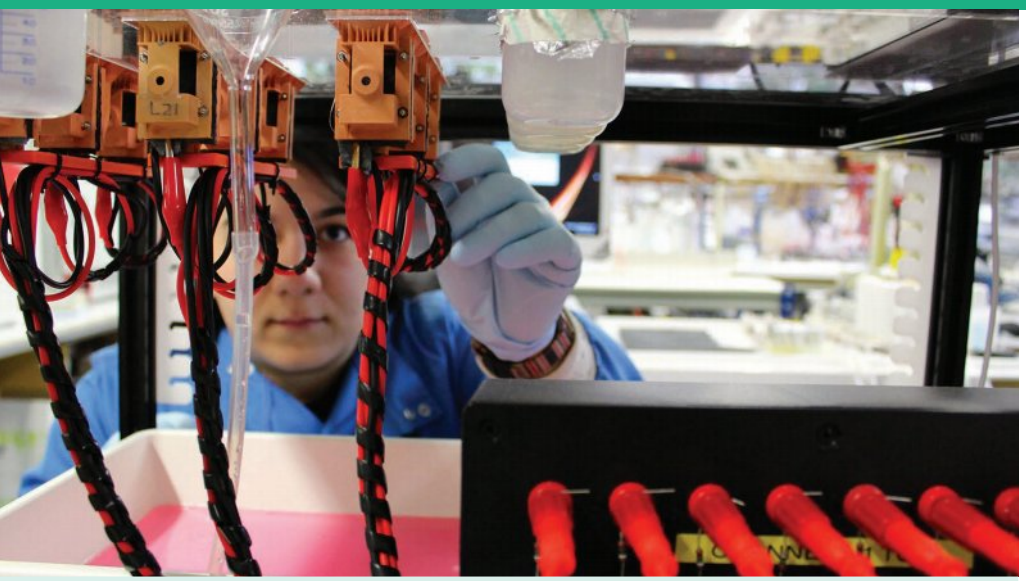
i. Advantage 1 MARK

ii. Disadvantage 1 MARK

FROM LESSONS 2A, 2C & 3E

Back to contents

3G Fuel cell challenges and innovations



Could using microbes in fuel cells help solve the energy crisis?

Some bacteria and other microbes can convert waste material to electrical energy that can be harnessed for use by humans: an innovative fuel cell that has the potential to be a major source of energy in the future. In this lesson, we will introduce the principles of **green chemistry** and the **Sustainable Development Goals** that help fulfil these principles. In particular, we will explore fuel cell innovations made to combat current challenges and meet society's demand for energy, including efficiency improvements and the use of **renewable** fuels.

STUDY DESIGN DOT POINT

- contemporary responses to challenges and the role of innovation in the design of fuel cells to meet society's energy needs, with reference to green chemistry principles: design for energy efficiency, and use of renewable feedstocks

3A 3B 3C 3D 3E 3F **3G**

- 3.1.19.1 Green chemistry principles - part 1
- 3.1.19.2 Design for energy efficiency
- 3.1.19.3 Renewable feedstocks

ESSENTIAL PRIOR KNOWLEDGE

1B Renewability of feedstocks

3E Fuel cells

See questions 29–30.

KEY TERMS AND DEFINITIONS

Feedstock raw material used for producing another product

Green chemistry set of principles aimed at reducing the use or production of harmful substances in chemical processes

Renewable resource resource capable of being replaced by natural processes within a relatively short period of time

Sustainable can be produced at a rate that is greater than or equal to the rate of consumption without compromising future generations

Sustainable Development Goals set of 17 objectives to promote a positive present and future for people and the planet

Green chemistry principles – part 1 3.1.19.1

In 1998, a set of 12 principles of 'green chemistry' were devised, aimed towards reducing the impact of chemical processes on the environment.[1] These principles play a key guiding role in modern chemistry.

Why should chemistry be 'green'?

Although chemistry plays a vital role in the production of energy, the development of medicines, and the manufacturing of products we use every day, chemical processes can also have harmful effects on health and the environment.

KEEN TO INVESTIGATE?

1 **What are the 12 principles of green chemistry?**
Search: 12 principles of green chemistry

In the 1990s, concern grew that if no considerations of the impact of antiquated chemical processes were made, resources would be depleted until they were all used up; waste on Earth would build up without end; water supplies would become more and more polluted; the atmosphere would be clogged with harmful gases; and energy would be wasted on inefficient chemical processes.

As a result, 12 internationally recognised principles of 'green chemistry' were developed, which focus on:

- designing processes to minimise raw material required and waste produced
- using renewable, safe, and environmentally harmless materials where possible
- maximising energy efficiency of reactions.

Furthermore, the United Nations have devised 17 Sustainable Development Goals (figure 1): global approaches to meet the needs of the present without compromising the ability of future generations to meet their own needs. Nine of these Goals are particularly relevant to VCE chemistry:

- Goal 2: Zero hunger
- Goal 6: Clean water and sanitation
- Goal 7: Affordable and clean energy
- Goal 9: Industry, innovation and infrastructure
- Goal 11: **Sustainable** cities and communities
- Goal 12: Responsible consumption and production
- Goal 13: Climate action
- Goal 14: Life below water
- Goal 15: Life on land.



Figure 1 The United Nations' 17 Sustainable Development Goals

In short, chemistry needs to be 'green' to protect the health of humans and ecosystems, to preserve the Earth and its atmosphere, and to ensure that future generations can continue to access and make innovations in chemistry.

PROGRESS QUESTIONS

Question 1

Which of the following does not align with green chemistry principles?

A. Burning plastic to reduce landfill.

B. Removing harmful chemicals from oceans.

C. Using hydrogen gas produced from renewable electricity as fuel.

D. Using and reusing materials to speed up chemical processes.

Question 2

A student proposes that their school laboratory re-uses chemicals across classes (where it is practical), rather than synthesising new chemicals for each class. This innovation is most closely related to which Sustainable Development Goal?

A. Goal 2: Zero hunger

B. Goal 6: Clean water and sanitation

C. Goal 7: Affordable and clean energy

D. Goal 12: Responsible consumption and production

Designing for energy efficiency 3.1.19.2

One of the 12 green chemistry principles is 'design for energy efficiency', and this is particularly relevant to the development and operation of fuel cells, as well as to the fulfilment of Sustainable Development Goals 7, 9, and 12.

How are fuel cells designed to maximise energy efficiency?

The energy efficiency of a fuel cell is the proportion of chemical energy in the fuel consumed that is converted to usable energy, and sources of inefficiency include heat loss and obstruction of current. A number of factors contribute to the energy efficiency of fuel cells, and many of these are active areas of research.

Use of catalysts

The electrodes in a fuel cell are coated with catalysts, which will be explored in detail in lesson 4B. Catalysts speed up reactions in fuel cells, decreasing the amount of time for energy to escape the system and be lost to the atmosphere, hence increasing energy efficiency. However, the most effective catalysts for use in many fuel cells are non-renewable metals including platinum, which is also extremely expensive. Researchers are continually investigating alternative catalyst materials to enhance their activity, stability, and cost-effectiveness.

Electrode porosity and nanomaterials

Fuel cell electrodes need to be porous to allow the diffusion of gaseous reactants (as discussed in lesson 3E). The smaller and more numerous these pores are, the higher the surface area of the electrodes and hence the greater the ability of reactants to come into contact with catalysts, enhancing efficiency. As a result, nanomaterials (materials whose dimensions are approximately 10^{-9} m), shown in figure 2, are used as electrodes in some fuel cells to maximise reaction efficiency, though many of these are still in development at a large scale.

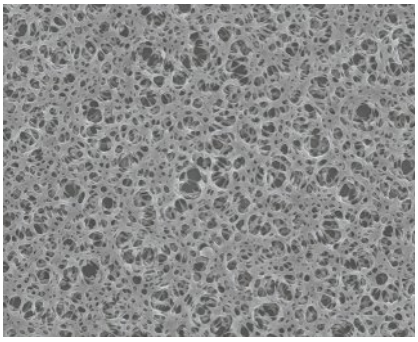


Image: DooDee Studio/Shutterstock.com

Figure 2 Extremely porous nanomaterial, magnified by a factor of ~10^7

Combined heat and power

For some applications, fuel cells can be used in combined heat and power setups (sometimes known as cogeneration), where heat, a by-product of the fuel cell, is captured and used to heat cars or buildings. In this way, the overall energy efficiency of the system is improved by making productive use of heat that would otherwise go to waste, but the usefulness of these heating setups is subject to the climate and the season (as heating is only desirable when it's cold!).

Hybrid systems

One source of inefficiency in fuel cells is that they continually produce energy so long as fuel is supplied, though at certain times, less energy may be required (known as variable demand), meaning that energy is left unconsumed and potentially wasted. However, fuel cells can be combined with other energy conversion and storage technologies such as batteries (which will be explored further in lesson 6C) to store this excess energy, minimising energy lost.

Polymer membrane electrolytes

The electrolyte in a fuel cell is crucial for ion transport and electrode separation. Many cells use membrane electrolytes, which are proton-conductive polymers designed to maximise the speed of ion movement and hence increase current efficiency (which will be explored further in lesson 6D). The use of polymers rather than aqueous solutions also prevents leakage and potential cross-contamination between fuel and oxidising agent streams. In addition, polymer membranes give the cell greater temperature resilience: while aqueous electrolytes may freeze in cold temperatures or evaporate if too hot, many membranes can operate at almost all temperatures. However, polymer membranes can be expensive to produce, and are derived from non-renewable crude oil.

MISCONCEPTION

'The protons conducted by a membrane electrolyte are always aqueous and are written as $H^+(aq)$.'

Since the proton is conducted across a solid membrane, it should not have any state symbol (just H^+); just like when an electron is involved in a half-equation, it also does not have a state symbol.

Operating conditions

Optimal conditions can vary depending on the type of fuel cell technology, but in general, higher temperatures and pressures increase the rate of fuel cell reactions and hence efficiency, as will be explained further in lesson 4A. However, maintaining high temperatures requires large amounts of energy, decreasing the net energy efficiency of the cell. Fuel cell designers often aim to use the heat produced by the fuel cell itself to heat the system, minimising the quantity of external energy required. They must find a compromise in conditions to balance cost, energy efficiency, and safety: a concept explored in lesson 5D.

Durability

The more frequently fuel cells need to be replaced, the more time they spend offline, and hence the lower their long-term efficiency. Currently, the average lifespan for fuel cells is currently around five years; for this reason, chemists are continually investigating more durable materials to use in fuel cells. One example is graphene, a nanomaterial and an allotrope of carbon (figure 3), which when sprinkled with platinum particles, is theoretically much more durable and equally effective as commercially available catalysts. This also reduces waste: another key principle of green chemistry.



Image: Production Perig/Shutterstock.com

Figure 3 Structure of a graphene nanotube, which can be used as a fuel cell catalyst

PROGRESS QUESTIONS

Question 3

Polymer membranes are used as electrolytes primarily because

A. they are usually cheaper to produce than solutions.

B. they can readily be produced from renewable sources.

C. they increase current efficiency.

D. they can only function at high temperatures.

Question 4

Fuel cell efficiency can be improved by

A. producing energy when it is not required.

B. using the by-product thermal energy for heating.

C. slowing down the rate of reaction.

D. removing the catalyst.

Renewable feedstocks 3.1.19.3

Many of the fuels used in traditional fuel cells – such as methane or most types of hydrogen fuel – are from non-renewable sources, potentially compromising future generations' access to this technology. In response, scientists are seeking to integrate renewable **feedstocks** into fuel cells: another key green chemistry principle.

How can fuel cells use renewable feedstocks to produce energy?

Renewable feedstocks for fuel cells include the biofuels studied in lesson 1B, such as bioethanol, or any other energy-yielding substances that can be replenished in short periods of time.

CO_2/H_2 fuel cell

Scientists have recently developed an experimental fuel cell that uses carbon dioxide gas, CO_2 (instead of the usual O_2) as the oxidising agent, and hydrogen gas, H_2, as the fuel. Carbon dioxide is renewable, since it is continually produced by humans and animals as they exhale, as well as being produced by the combustion of biomass; hydrogen gas can also be renewable, as explored in lesson 6D. A diagram of this fuel cell is shown in figure 4.

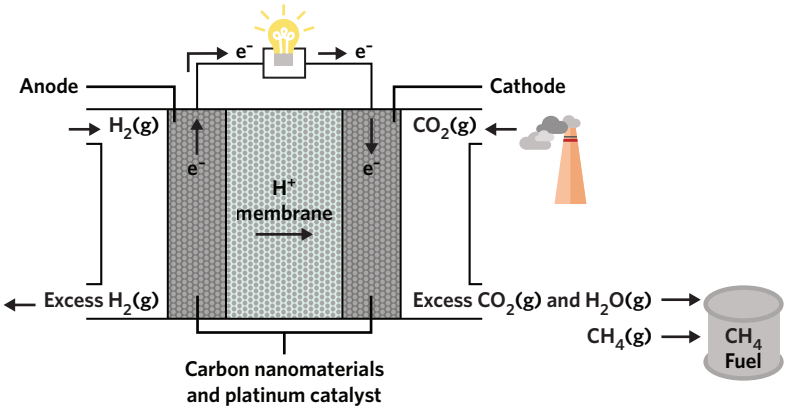


Figure 4 CO_2/H_2 fuel cell, producing CH_4 fuel

This CO_2/H_2 fuel cell uses a polymer membrane, carbon nanotubes, and platinum nanoparticles to produce electrical energy, all while consuming CO_2 and hence removing it from the atmosphere. The possible half-equations for this fuel cell are as follows.

Anode: $H_2(g) \rightarrow 2H^+ + 2e^-$

Cathode:

- $CO_2(g) + 4H^+ + 4e^- \rightarrow C(s) + 2H_2O(g)$
- $CO_2(g) + 6H^+ + 6e^- \rightarrow CH_3OH(g) + H_2O(g)$
- $CO_2(g) + 8H^+ + 8e^- \rightarrow CH_4(g) + 2H_2O(g)$
- $2CO_2(g) + 12H^+ + 12e^- \rightarrow CH_2CH_2(g) + 4H_2O(g)$
- $2CO_2(g) + 12H^+ + 12e^- \rightarrow CH_3CH_2OH(g) + 3H_2O(g)$

A number of possible carbon-based chemicals, such as methane, are produced in this reaction, and these can be used to produce further energy via combustion or a different fuel cell; however, doing so negates the 'CO_2-absorbing' property of this fuel cell, as CO_2 is consequently produced.

Bioethanol fuel cell

Vehicle manufacturers are currently experimenting with the use of bioethanol fuel cell-powered vehicles, particularly in regions with existing bioethanol infrastructure such as Brazil and Thailand. Bioethanol is a biofuel that can be produced from corn and sugarcane crops, and since bioethanol is functionally identical to any 'other' ethanol, the half-reactions for this cell are the same as those of the direct ethanol fuel cell (DEFC) mentioned in lesson 3E:

Oxidation (anode): $C_2H_5OH(l) + 3H_2O(l) \rightarrow + 2CO_2(g) + 12H^+ + 12e^-$

Reduction (cathode): $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l)$

Overall: $C_2H_5OH(l) + 3O_2(g) \rightarrow 6H_2O(l) + 2CO_2(g)$

Due to their generally lower operating temperatures, fuel cells tend to produce lower emissions of harmful sulphur- and nitrogen-containing compounds.

Microbial fuel cell

Although the aforementioned fuel cells use renewable fuels and oxidising agents, the precious metals used as their catalysts are non-renewable and expensive to produce, reducing their large-scale feasibility. In contrast, microbial biofuel cells involve bacteria, which use their enzymes (biological catalysts, covered in further detail in lesson 11B) to speed up the oxidation of renewable, plant-based fuels such as glucose, shown in the following oxidation half-equation.

Glucose: $C_6H_{12}O_6(aq) + 6H_2O(l) \rightarrow 6CO_2(g) + 24H^+ + 24e^-$

Any organic feedstock that can be broken down by bacteria, such as wastewater or compost, can be used as 'fuel' in these cells.[2] Clean water can be produced as a by-product of microbial wastewater treatment fuel cells, providing another useful resource. The oxidation half-equation for the breakdown of wastewater is as follows.

Domestic wastewater:
$C_{10}H_{19}O_3N(aq) + 18H_2O(l) \rightarrow 9CO_2(g) + NH_4^+(aq) + HCO_3^-(aq) + 50H^+ + 50e^-$

A microbial fuel cell that converts energy stored in the bonds of ethanoic acid to electrical energy using a soil electrolyte is shown in figure 5.

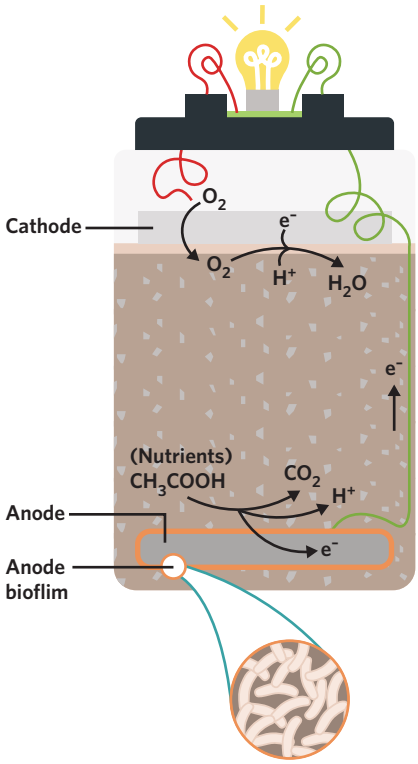


Figure 5 Soil microbial fuel cell

KEEN TO INVESTIGATE?

[2] **How can you make your own microbial fuel cell?**
Search YouTube: Creating a Microbial Fuel Cell

How sustainable is the use of renewable feedstocks?

Just because feedstocks are renewable (able to be replenished in a short period of time), does not necessarily mean they are sustainable (able to be produced at the same or greater rate than they are consumed). For example, bioethanol is produced from crops such as corn; yet to meet society's massive demand for energy, these crops need to be continually harvested and replanted, an intensive process which is unsustainable for the soil. Moreover, if land previously used for growing food crops is replaced with land for growing bioethanol crops, this may render food supply to humans unsustainable. In this case, bioethanol would be classed as a 'first generation' biofuel; the generations of biofuels are summarised in table 1 and explored further in lesson 8B.

Table 1 Generations of biofuels

Generation	Feedstock source	Sustainability factors
First	Edible crops, such as corn, wheat, sugarcane, and soybean	• Intensive farming required to meet demand, potentially damaging soil • Competes with valuable food sources
Second	Non-food crops and waste materials, such as grasses and household waste	• Waste is readily available • Difficult to convert biomass to conventionally usable fuels
Third	Algae and other microbes	• High productivity and potential to absorb CO_2 from the atmosphere • Prohibitively difficult to process to match energy demand (as it stands)
Fourth (emerging)	Cyanobacteria	• High productivity and potential to absorb CO_2 from the atmosphere • Prohibitively difficult to process to match energy demand (as it stands)

WORKED EXAMPLE 1

An experimental fuel cell uses algae grown in a laboratory to produce electrical energy.

In contrast, most global ethanol is currently produced by intensive cultivation of crops that could otherwise be used as food. This ethanol can likewise be used as a fuel in a fuel cell.

Evaluate which of these two sources produces a more sustainable feedstock for a fuel cell, with specific reference to two of the Sustainable Development Goals.

What information is presented in the question?

The algae used in the fuel cell is lab-grown.

The ethanol used in the fuel cell is intensively harvested from food crops.

What is the question asking us to do?

Evaluate which of lab-grown algae or bioethanol is a more sustainable feedstock.

What strategies do we need in order to answer the question?

1. Define sustainability.
2. Evaluate the sustainability of both methods of energy production.
3. Identify two Sustainable Development Goals relevant to the sustainability of these two energy production methods.

Answer

Sustainability refers to how quickly or feasibly the resource can be produced, relative to the rate at which it is consumed.

Algae is likely to be sustainable if it can be produced in a laboratory at a sufficient rate to meet demand.

Bioethanol is unlikely to be sustainable due to the long-term impact of intensive farming on plants and animals (Goal 15) and the need to retain land area for growing crops for food (Goal 2), not just for fuel.

Hence, algae is a more sustainable option, as it does not detract from food availability in the long term, helping to achieve Goal 2: Zero hunger, and it does not require intensive cultivation that damages land ecosystems, helping to achieve Goal 15: Life on land.

PROGRESS QUESTIONS

Question 5

Which of the following is **not** a renewable feedstock for a fuel cell?

A. Bioethanol

B. Wastewater

C. Platinum

D. Carbon dioxide

Question 6

The sustainability of a feedstock depends on

A. how quickly it can be replenished.

B. the rate at which it is consumed.

C. how easily it can be produced.

D. All of the above

Theory summary

- Green chemistry principles guide chemists to minimise the impact of chemical processes on humans, the environment, and future generations.
- A key aim of chemical innovation is to help achieve the Sustainable Development Goals.
- A number of factors contribute to the energy efficiency of fuel cells, including:
  - the use of catalysts, porous electrodes, and nanomaterials
  - the operating conditions of fuel cells and their durability
  - the selection of electrolyte materials including membranes
  - the combination of fuel cells with other energy conversion or heating systems.
- The use of renewable feedstocks, such as biofuels or green hydrogen, is another active fuel cell research area, aimed at ensuring future generations' access to fuel cells.
- Using microbes in fuel cells shows promise in contributing to solving the energy crisis; it should be seen as one piece of the larger puzzle involving multiple renewable energy technologies.

3G Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

Currently, there is huge demand for vehicle engines, but fuel cells do not hold a huge share of the market. A car manufacturer has enlisted you with the task of suggesting ways to overcome current barriers to fuel-cell powered vehicles.

Question 7 (1 MARK)

The main factor behind the high (monetary) cost of fuel cells compared with traditional engines is

A. the price of fuel.

B. the cost of the precious metal catalysts.

C. the expense related to continual maintenance.

D. the need to replace anode metals when they are used up.

Question 8 (1 MARK)

One barrier faced by hydrogen fuel cells is that

A. hydrogen storage poses safety and efficiency issues.

B. hydrogen cannot be produced from renewable sources.

C. these fuel cells still emit large quantities of CO_2 when operating.

D. these fuel cells currently only exist in concept, and not in practice.

Question 9 (2 MARKS)

In response to the major challenges this technology currently faces, suggest two innovations to potentially boost adoption of fuel cell vehicles, while maintaining or improving cell efficiency.

Exam-style

Question 10 (4 MARKS)

A ski lodge wishes to improve the sustainability of its practices. Its owners are considering powering the lodge with a fuel cell. List two considerations or innovations that the ski lodge could make to maximise the fuel cell's efficiency, and explain why they are appropriate for a ski lodge.

Question 11 (4 MARKS)

The following information on PEM fuel cells appeared in a science magazine.

> A proton exchange membrane (PEM) fuel cell converts hydrogen gas to electrical energy, and involves the following half-equations.
>
> $H_2(g) \rightarrow 2H^+ + 2e^-$
>
> $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l)$
>
> This fuel cell utilises a polymer membrane electrolyte, which lasts for approximately 1 year when operating at temperatures of approximately 80 °C. Scientists believe that this fuel cell has the potential to be used for transport vehicles as well as power generation in cities. PEM fuel cells can be purchased for around $100.

a. Identify one aspect of the PEM fuel cell that aligns with green chemistry principles, linking this aspect to a Sustainable Development Goal. 2 MARKS

b. Identify one area for improvement of the PEM fuel cell to better align with green chemistry principles, linking this improvement to a different Sustainable Development Goal from your answer to part **a**. 2 MARKS

Question 12 (5 MARKS)

Enzymatic biofuel cells are similar to microbial fuel cells, but instead of using bacteria themselves, they use enzymes extracted from biological organisms to speed up the oxidation of a biofuel.

a. One property of enzymes is that they are specific, meaning they are only able to catalyse (speed up) one reaction; for example, hydrogenase can only catalyse the oxidation of H_2.

i. Explain why this property increases the efficiency of enzymatic biofuel cells. 1 MARK

ii. Identify one other advantage of using enzymes, rather than precious metals like platinum, as catalysts. 1 MARK

b. A major advantage of enzymatic biofuel cells is that they use renewable feedstocks. Explain what this means in the context of fuel cells, and evaluate the sustainability of renewable feedstocks. 3 MARKS

Key science skills

Question 13 (6 MARKS)

Refer to the following information and your knowledge of fuel cell innovation to answer the question.

Green chemistry principles:

- Prevent waste: Design chemical processes to prevent waste. Leave no waste to treat or clean up.
- Catalysis: Catalysts should be selected to generate the same desired product(s) with less waste while using less energy and reagents in reaction processes/pathways.
- Designing safer chemicals: Chemical processes should be designed to achieve their intended function while minimising the use or production of toxic chemicals.
- Minimise the potential for accidents: Design chemicals and their physical forms (solid, liquid, or gas) to minimise the potential for chemical accidents including explosions, fires, and releases to the environment.

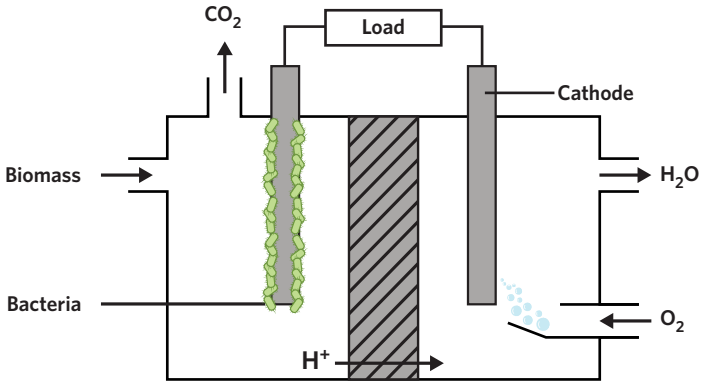
Select three of the green chemistry principles given. Explain how fuel cell innovation helps fulfil each principle, with the aid of a specific example of innovation for each.

FROM LESSON 12E

Questions from multiple lessons

Question 14 (8 MARKS)

Microbial fuel cells, MFC, use bacteria to metabolise biomass. The MFC anode has bacteria growing on it. The bacteria decompose organic matter and produce H^+ ions and electrons. The bacteria transfer electrons directly to the anode. One half-cell has oxygen bubbled into it. In the other half-cell, oxygen is excluded. A diagram of an MFC is given.



a. In an MFC, the bacteria decompose biomass, in the absence of oxygen, through a process called anaerobic cellular respiration.

i. Write the equation for respiration that occurs in the cells of the human body. 1 MARK

ii. Sketch the energy profile diagram for respiration. No scale is required. 1 MARK

b. Write the balanced half-equation for the reaction occurring at the cathode. 1 MARK

c. Explain why the two half-cells are separated. 2 MARKS

d. A galvanic cell can be constructed from a $Ni^{2+}(aq)$ | Ni(s) half-cell and an $Ag^+(aq)$ | Ag(s) half-cell.

i. State the maximum cell voltage, under standard conditions, of the $Ag^+(aq)$ | Ag(s) || $Ni^{2+}(aq)$ | Ni(s) galvanic cell. 1 MARK

ii. Write the overall equation (including states) for the $Ag^+(aq)$ | Ag(s) || $Ni^{2+}(aq)$ | Ni(s) galvanic cell. 1 MARK

iii. State an advantage of an MFC over the $Ag^+(aq)$ | Ag(s) || $Ni^{2+}(aq)$ | Ni(s) galvanic cell. 1 MARK

Adapted from VCAA (NHT) Short answer 2023 exam Q3

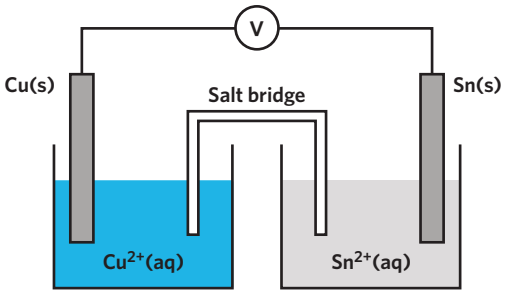
FROM LESSONS 1C, 1D, 3B & 3D

Chapter 3 review

Multiple choice (10 MARKS)

Use the following information to answer questions 1–3.

A galvanic cell set up under standard conditions is shown.



Question 1 (1 MARK)

Which of the following correctly completes the two statements?

	As the cell discharges, electrons would flow from the	In the salt bridge,
A.	tin electrode to the copper electrode.	anions migrate to the Cu^{2+}/Cu half-cell.
B.	copper electrode to the tin electrode.	cations migrate to the Sn^{2+}/Sn half-cell.
C.	copper electrode to the tin electrode.	cations migrate to the Cu^{2+}/Cu half-cell.
D.	tin electrode to the copper electrode.	anions migrate to the Sn^{2+}/Sn half-cell.

Adapted from VCAA 2012 Exam 2 Multiple choice Q16

Question 2 (1 MARK)

In this cell,

A. $Cu^{2+}(aq)$ is reduced, and Sn(s) is oxidised.

B. Cu(s) is oxidised, and $Sn^{2+}(aq)$ is reduced.

C. Cu(s) is reduced, and $Sn^{2+}(aq)$ is oxidised.

D. $Cu^{2+}(aq)$ is oxidised, and Sn(s) is reduced.

Adapted from VCAA 2012 Exam 2 Multiple choice Q17

Question 3 (1 MARK)

The maximum voltage produced by this cell, under standard conditions, is

A. +0.16 V

B. +0.48 V

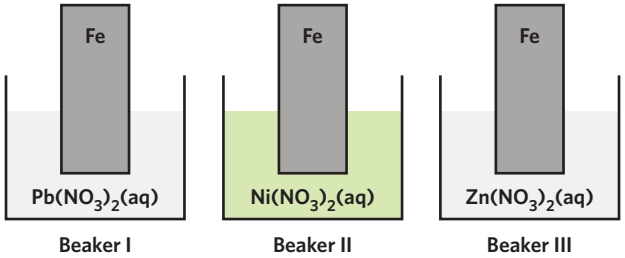
C. +0.19 V

D. +0.49 V

Adapted from VCAA 2012 Exam 2 Multiple choice Q18

Question 4 (1 MARK)

Three beakers, each containing an iron strip and a 1.0 M solution of a metal salt, were set up as shown.



A reaction will occur in beaker(s)

A. I and II only.

B. I and III only.

C. II and III only.

D. III only.

VCAA 2013 exam Multiple choice Q24

Question 5 (1 MARK)

Which of the following fuel cell innovations is most likely to be unsustainable?

A. Using wastewater as a feedstock

B. Using CO_2 as an oxidising agent instead of O_2

C. Using bioethanol produced from crops previously used for food

D. Using carbon nanoparticles in an electrode to speed up the reaction

---

Question 6 (1 MARK)

The overall equation for a particular methanol fuel cell is shown.

$2CH_3OH(g) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$

The equation for the reaction that occurs at the cathode in this fuel cell is

A. $CO_2(g) + 5H_2O(l) + 6e^- \rightarrow CH_3OH(g) + 6OH^-(aq)$

B. $CH_3OH(g) + 6OH^-(aq) \rightarrow CO_2(g) + 5H_2O(l) + 6e^-$

C. $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$

D. $4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^-$

VCAA 2017 exam Multiple choice Q6

Question 7 (1 MARK)

Hydrogen peroxide solutions are commercially available and have a range of uses. The active ingredient, hydrogen peroxide, H_2O_2, undergoes decomposition in the presence of a suitable catalyst according to the following reaction.

$2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g)$

In this reaction, oxygen

A. only undergoes oxidation.

B. only undergoes reduction.

C. undergoes both oxidation and reduction.

D. undergoes neither oxidation nor reduction.

VCAA 2016 exam Multiple choice Q3

Question 8 (1 MARK)

The discharge reaction in a vanadium redox battery is represented by the following equation.

$VO_2^+(aq) + 2H^+(aq) + V^{2+}(aq) \rightarrow V^{3+}(aq) + VO^{2+}(aq) + H_2O(l)$

When the vanadium redox battery is recharging,

A. H^+ is the reducing agent.

B. H_2O is the oxidising agent.

C. VO^{2+} is the reducing agent.

D. VO_2^+ is the oxidising agent.

VCAA 2022 exam Multiple choice Q14

Question 9 (1 MARK)

Consider the following statements about galvanic cells and fuel cells.

Statement number	Statement
1	The overall reaction is exothermic.
2	Electrons are consumed at the negative electrode.
3	Both the reducing agent and the oxidising agent are stored in each half-cell.
4	The electrodes are in contact with the reactants and the electrolyte.
5	The production of electricity requires the electrodes to be replaced regularly.

Which one of the following sets of statements is correct for both galvanic cells and fuel cells?

A. Statements 2 and 3 only

B. Statements 1 and 4 only

C. Statements 2, 4, and 5 only

D. Statements 1, 3, and 5 only

VCAA 2019 exam Multiple choice Q8

Question 10 (1 MARK)

A hydrogen-oxygen fuel cell uses 2.9×10^{-4} mol of hydrogen gas per second of operation.

The current produced by this cell is

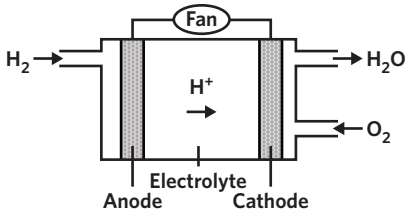
A. 2.9 A **B.** 5.8 A **C.** 28 A **D.** 56 A

Adapted from VCAA 2014 exam Multiple choice Q29

Short answer (30 MARKS)

Question 11 (6 MARKS)

Consider the fuel cell shown.



Assuming standard laboratory conditions, if a fan powered by this fuel cell is supplied with an average current of 6.00 A, and the fuel cell and the device are connected for 12.0 hours:

a. What quantity of charge is expected to flow through the fuel cell as it operates? 1 MARK

b. How many moles of electrons are predicted to be produced at the anode of this cell? 1 MARK

c. If the cell operates at 60% efficiency, how many moles of electrons are produced at the anode? 1 MARK

d. Write the half-equation for the reaction that occurs at the anode of this fuel cell. 1 MARK

e. How many moles of hydrogen gas are consumed at the anode if the cell operates at 60% efficiency? 1 MARK

f. What volume of hydrogen gas is consumed by this cell, assuming it operates at 60% efficiency? 1 MARK

Question 12 (3 MARKS)

A student made the following notes about a phosphoric acid fuel cell using information obtained from various texts and websites.

Electrolyte: *Liquid phosphoric acid.* H_3PO_4

Equations

Anode reaction: $H_2(g) \rightarrow 2H^+$ *(in phosphoric acid)* $+ 2e^-$

Cathode reaction: $O_2(g) + 4H^+$ *(in phosphoric acid)* $+ 4e^- \rightarrow 2H_2O(g)$

Operating temperature: 190 °C

The student also made the following notes regarding the electrochemical series.

It is possible to predict the voltage output of a standard cell by using E^o *values and the formula*

Cell voltage = E^o*(cathode equation) –* E^o*(anode reaction)*

Using the following equations and E^o *values from the electrochemical series*

$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$ $\quad E^o = +1.23$ V

$2H^+(aq) + 2e^- \rightarrow H_2(g)$ $\quad E^o = 0.00$ V

Phosphoric acid fuel cell voltage = E^o*(cathode reaction) –* E^o*(anode reaction)*

$= +1.23$ V $- 0.00$ V

$= +1.23$ V

Hence the predicted voltage according to the electrochemical series is 1.23 V.

However, the actual voltage produced by this fuel cell is 0.70 V.

a. Give two specific reasons as to why the phosphoric acid fuel cell does not produce the +1.23 V predicted by the student. 2 MARKS

b. Write a balanced equation for the overall reaction that occurs in the phosphoric acid fuel cell. 1 MARK

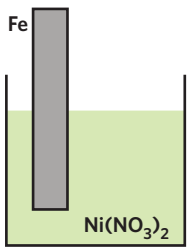
VCAA 2010 Exam 2 Short answer Q8

Question 13 (6 MARKS)

Energy can be produced in a variety of ways, including from galvanic cells, fuel cells, and gas-fired power stations. Each of these methods suits particular applications.

Galvanic cells and fuel cells are methods of energy production that are based on redox reactions, similar to the reaction that would occur in Setup A shown. Setup A consists of a beaker with a strip of iron, Fe, in a solution of nickel(II) nitrate, $Ni(NO_3)_2$.

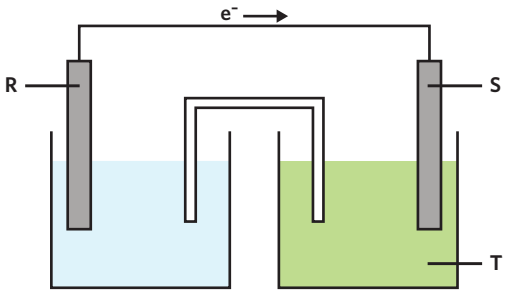
Setup A



a. Identify the reducing agent for the reaction that would occur in Setup A. 1 MARK

b. Batteries made up of primary galvanic cells, such as the one in Setup B shown, have traditionally been used in small electrical devices. Setup B consists of a galvanic cell based on the redox reaction in Setup A.

Setup B



i. Identify appropriate materials for electrodes R and S in Setup B. 2 MARKS

ii. Write an appropriate chemical formula for solution T in Setup B. 1 MARK

c. Identify the main energy conversions that take place in

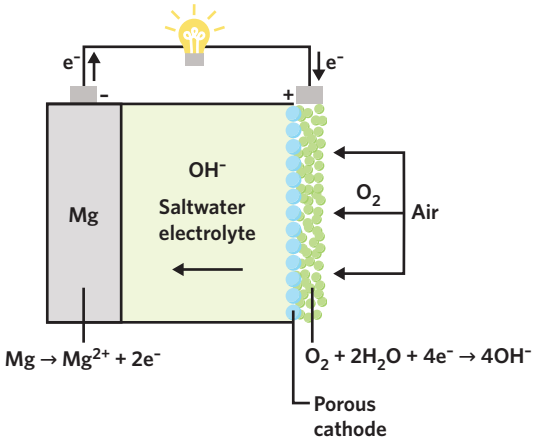
i. Setup A. 1 MARK

ii. Setup B. 1 MARK

Adapted from VCAA (NHT) 2019 exam Short answer Q5

Question 14 (8 MARKS)

Magnesium-air batteries are electrochemical cells that share some features in common both with fuel cells and with other (non-fuel) galvanic cells.



a. Identify one feature of the magnesium-air battery that is a key feature of:

i. Fuel cells 1 MARK

ii. Other (non-fuel) galvanic cells 1 MARK

b. Magnesium-air batteries have been considered for use in wearable devices, such as smartwatches. When in operation, the magnesium anode is consumed, and eventually needs to be replaced. If a smartwatch requires a current of 1.22 A to operate, for how long (in seconds) can the smartwatch operate if it consumes 1.83 g of its magnesium anode? Assume 100% efficiency. 4 MARKS

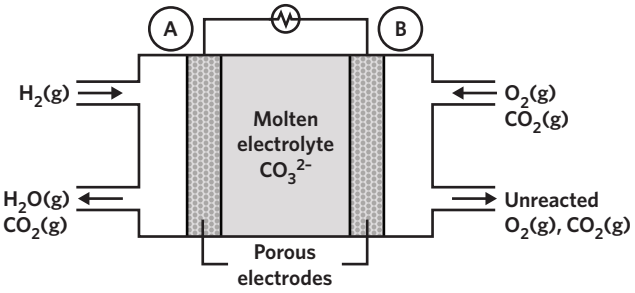
c. Of the materials used in the magnesium-air battery given, briefly explain one:

i. Material that can be produced sustainably 1 MARK

ii. Non-renewable material 1 MARK

Question 15 (7 MARKS)

Molten carbonate fuel cells (MCFCs) can be used as a stationary energy source. They operate at temperatures between 600 °C and 700 °C. The electrolyte in an MCFC is typically a molten mixture of lithium, sodium or potassium carbonates. A simplified diagram of an MCFC is shown.



At one electrode of the MCFC, carbon dioxide, CO_2, gas reacts with oxygen, O_2, gas to form carbonate ions. At the other electrode, hydrogen, H_2, gas reacts with molten carbonate ions to form steam and CO_2 gas.

a. For the cell shown,

i. Identify the respective polarities of electrodes A and B. 1 MARK

ii. In which direction do the electrons flow in the external circuit? 1 MARK

b. On a small scale, electricity can be generated in a variety of ways. What is **one** advantage of producing electricity from an MCFC rather than from a petrol generator? 1 MARK

c. Consider the reactions occurring in an MCFC.

i. Write a balanced half-equation for the production of carbonate ions from CO_2 and O_2. 1 MARK

ii. Under the conditions in this fuel cell, 1 mol of O_2 gas occupies 30.8 L. Calculate the volume of O_2 gas needed to produce 11.50 mol of carbonate ions. 3 MARKS

Adapted from VCAA (NHT) 2017 exam Short answer Q7

Key science skills (10 MARKS)

Question 16 (9 MARKS)

Sustainability is becoming an increasingly central focus of chemical innovation, including in the area of energy production. Six key Sustainable Development Goals are given.

- Goal 2: Zero hunger
- Goal 6: Clean water and sanitation
- Goal 7: Affordable and clean energy
- Goal 11: Sustainable cities and communities
- Goal 12: Responsible consumption and production
- Goal 13: Climate action

a. In one sentence, summarise why chemists need to consider green chemistry principles. 1 MARK

b. Scientists are experimenting with the use of microbes in fuel cells to oxidise wastewater via a membrane electrolyte, producing electrical energy and treated water.

Fuel cells that use CO_2 (instead of oxygen) to oxidise a fuel and hence produce energy are also in development. A major reduction half-reaction occurring in these fuel cells is as follows.

$$CO_2(g) + 6H^+(aq) + 6e^- \rightarrow CH_3OH(aq) + H_2O(l) \quad E^0 = +0.016\ V$$

For each of these two fuel cell innovations:

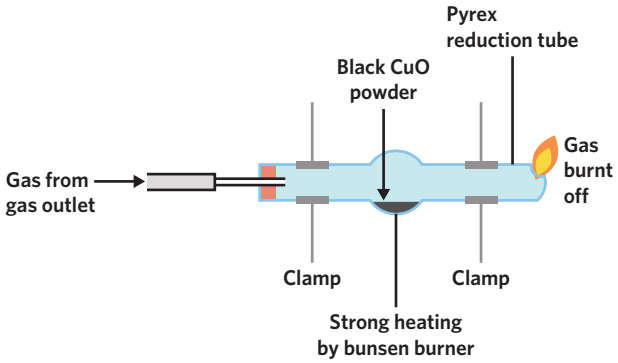
i. Identify one Sustainable Development Goal (from the list given) that this innovation helps achieve, and explain how it contributes to this goal. 4 MARKS

ii. Evaluate this innovation, identifying one challenge faced. 4 MARKS

FROM LESSON 12E

Question 17 (1 MARK)

Some students conducted an experiment to determine the percentage by mass of copper in copper(II) oxide. The apparatus they used is shown in the diagram.



The equation for the redox reaction is

$2CuO(s) \rightarrow 2Cu(s) + O_2(g)$

The gas passing through the tube prevented the copper from re-oxidising to CuO.
The students weighed:

1. the empty tube
2. the tube and CuO before heating
3. the tube and Cu after heating and cooling.

They found that the percentage by mass of copper in the copper oxide was 76.42%. The theoretical value is 79.86%. Which one of the following could **not** be a possible explanation for the lower experimental result?

A. The copper(II) oxide, which is black, was contaminated with some carbon.

B. Some copper(II) oxide remained unreacted when heating was stopped.

C. Contamination on the outside of the tube was burnt off during the heating.

D. Some of the copper(II) oxide powder was blown out of the tube by the gas.

VCAA 2014 exam Multiple choice Q30

FROM LESSONS 12A & 12B

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UNIT 3 AOS 2

How can the rate and yield of chemical reactions be optimised?

In this area of study, students explore the factors that affect the rate and yield of equilibrium and electrolytic reactions involved in producing important materials for society. Reactants and products in chemical reactions are treated qualitatively through the application of Le Chatelier's principle and quantified using equilibrium expressions, reaction quotients and Faraday's Laws. Students explore the sustainability of different options for producing useful materials for society.

The selection of learning contexts should allow students to develop practical techniques to investigate equilibrium and electrolysis. Students develop their skills in the use of scientific equipment and apparatus. They investigate reaction rates including the measurement of mass, gas volumes and time. They use an equilibrium system, such as iron(III) thiocyanate, to predict and test the effect of different changes to the system. They investigate the effect of catalysts on reaction rates, such as comparing the rate of decomposition of hydrogen peroxide using organic and inorganic catalysts.

Students explore the application of electrolysis in the manufacture of useful products through experiments such as electroplating and anodising. They model and explain the operation of secondary cells: for example, those in portable devices such as laptops or cell phones. Students respond to challenges such as predicting and testing the optimum conditions under which a selected reaction can produce the highest product yield.

Outcome 2

On completion of this unit the student should be able to experimentally analyse chemical systems to predict how the rate and extent of chemical reactions can be optimised, explain how electrolysis is involved in the production of chemicals, and evaluate the sustainability of electrolytic processes in producing useful materials for society.

Reproduced from VCAA VCE Chemistry Study Design 2024–2027

Image: emre topdemir/Shutterstock.com

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4

CHAPTER 4
Rates of chemical reactions

LESSONS

4A Factors affecting the rate of reaction

4B Catalysts

Chapter 4 review

KEY KNOWLEDGE

- factors affecting the frequency and success of reactant particle collisions and the rate of a chemical reaction in open and closed systems, including temperature, surface area, concentration, gas pressures, presence of a catalyst, activation energy and orientation
- the role of catalysts in increasing the rate of specific reactions, with reference to alternative reaction pathways of lower activation energies and represented using energy profile diagrams

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4A Factors affecting the rate of reaction

STUDY DESIGN DOT POINT

- factors affecting the frequency and success of reactant particle collisions and the rate of a chemical reaction in open and closed systems, including temperature, surface area, concentration, gas pressures, presence of a catalyst, activation energy and orientation

4A 4B

3.2.1.1 Collision theory

3.2.1.2 Effect of temperature on reaction rate

3.2.1.3 Effect of surface area on reaction rate

3.2.1.4 & 3.2.1.5 Effect of pressure on reaction rate & effect of concentration on reaction rate

ESSENTIAL PRIOR KNOWLEDGE

- Gas laws

1D Activation energy

See questions 31–32.



Image: Retouch man/Shutterstock.com

Why does carbon take over 1 billion years to naturally form diamond?

Some reactions are instant, whereas others may proceed slowly over millions of years, or even billions of years in the case of diamond formation. Chemical reactions occur when particles collide with sufficient energy and in a specific orientation. In this lesson, we will learn about the factors that affect the rate of these 'successful' reactions through **collision theory**.

KEY TERMS AND DEFINITIONS

Closed system a system in which energy can enter or leave, but matter cannot

Collision theory a theoretical model that explains the rates of chemical reactions in terms of collisions between particles

Kinetic energy the energy that a particle has due to its motion

Open system a system in which both matter and energy can enter or leave

Proportion the percentage of species with the necessary activation energy to react in a fixed sample

Reaction rate the change in concentration of a reactant or product over a period of time

Surface area the total area of all reacting particles available for collisions with other reactants

Collision theory 3.2.1.1

Collision theory describes the conditions required for a chemical reaction to occur.

What makes a collision successful?

For a chemical reaction to occur, particles must collide with each other with enough energy to break bonds within reactant particles, subsequently allowing these intermediate particles to form new products. Collisions that allow products to be formed are known as successful collisions, and will only occur if the following conditions are met:

1. Reactants must physically collide with each other.
2. Reactants must collide with sufficient energy to break the bonds within them (activation energy, E_a).
3. Reactants must collide with the correct orientation for bonds to actually break.

Firstly, the reactants must actually physically collide with another to react. Then, the reactants must collide with sufficient energy to break the existing bonds; as we learned in 1D, this amount of energy is known as activation energy and is denoted by E_a. The minimum activation energy for a given reaction to occur serves as a threshold, and if this threshold is met, then reactants must collide with a certain orientation in order for bonds to break.

Using the conditions listed above, we can better understand the factors affecting **reaction rates**. That is, how many moles of products will be formed or how many moles of reactants are used up in a given period of time. Since reactants need to collide with the necessary energy and orientation in order to react, we know that the more frequently they collide, the greater the chance of a successful collision, which results in an increased reaction rate. Similarly, we know that as the **proportion** of reactants with sufficient activation energy (E_a) increases, so too will the proportion of successful collisions.

PROGRESS QUESTIONS

Question 1

Which one of the following statements about collision theory is correct?

A. The frequency of collisions is independent of the energy of the molecules.

B. The frequency of collisions depends on the orientation of the molecules.

C. The chance of a collision resulting in a reaction depends on the orientation of the molecules.

D. The chance of a collision resulting in a reaction depends only on the kinetic energy of the molecules.

Adapted from VCAA (NHT) 2022 exam Multiple choice Q7

Effect of temperature on reaction rate 3.2.1.2

The temperature of a substance is representative of the average **kinetic energy** of the particles within the substance.

How does temperature affect reaction rate?

As the temperature of a reaction system increases, the reaction rate will increase also. This occurs in part due to reactants colliding more frequently due to increased average kinetic energy. Additionally, because the number of reactants with enough energy to surpass the activation energy threshold increases, there will be a greater proportion of successful collisions. The resultant increase in the reaction rate due to increased temperature can be represented in concentration versus time graphs (figure 1).

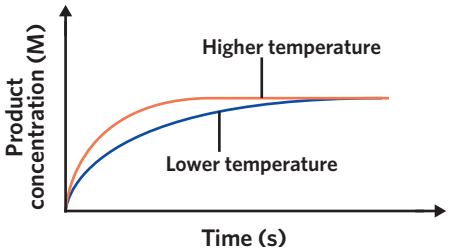
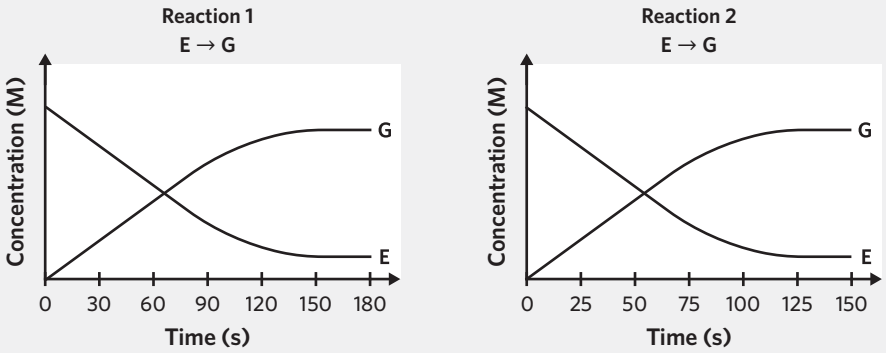


Figure 1 The relationship between reaction rate and temperature

In figure 1, we know that the reaction rate has increased at the higher temperature as the reaction has reached completion more quickly.

WORKED EXAMPLE 1

The diagrams provided show concentration versus time graphs for two reactions, one occurring at a higher temperature than the other. All other conditions are identical.



Which of the two reactions occurs at a higher temperature?

What information is presented in the question?

The concentration versus time graphs for the same reaction occurring at two different temperatures.

What is the question asking us to do?

Use the graphs to determine which of the graphs is occuring at a higher temperature.

What strategies do we need in order to answer the question?

1. Recall that reaction rate increases as temperature increases.
2. Use the graphs to determine which reaction is occuring more quickly (plateaus sooner).

Answer

The graphs appear identical, however, the scales of the two x-axes are slightly different. Therefore, for reaction 1, we can see that the reaction reaches completion at approximately 150 seconds, and for reaction 2, we can see that the reaction reaches completion at approximately 120 seconds. Therefore, reaction 2 has occurred at a faster rate, and must therefore be occurring at a higher temperature.

Adapted from VCAA (NHT) 2019 exam Multiple choice Q19

USEFUL TIP

When dealing with gaseous reactants in VCE chemistry, we assume that when the temperature of a gas changes, the pressure and volume remain constant.

PROGRESS QUESTIONS

Question 2

At lower temperatures, a reaction will occur more slowly because the

A. reactant particles collide more frequently.

B. reactant particles collide in the incorrect orientation.

C. reactant particles have a lower average kinetic energy.

D. reaction has a lower activation energy.

Question 3

The two statements below give possible explanations for changes that occur when the temperature of a reaction mixture is increased.

I. At a higher temperature, particles move faster and the reactant particles collide more frequently.

II. At a higher temperature, more particles have energy greater than the activation energy.

Which alternative below best explains why the observed reaction rate is greater at higher temperatures?

A. I only

B. II only

C. I and II to an equal extent

D. I and II, but II to a greater extent than I

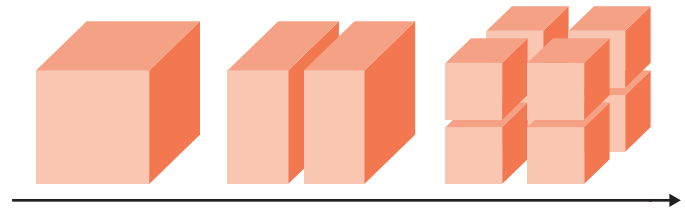
VCAA 2009 Exam 2 Multiple choice Q2

Effect of surface area on reaction rate 3.2.1.3

The **surface area** of a reactant refers to how much area a solid has available to collide with other reactants.

How does surface area affect reaction rate?

The rates of certain reactions can be altered by manipulating the size of the reactant particles. As shown in figure 2, when reactants are divided into smaller parts, they have more overall surface area.[1] In the case of a solid reactant sample, when its surface area increases, reactant particles can collide more frequently, resulting in more successful collisions over a given period of time, and thus a faster reaction rate.[2]



The smaller the reactant particles, the greater the total surface area available for collisions with reactants.

Figure 2 A cube being split into a powder (divided up) to increase its surface area

KEEN TO INVESTIGATE?

[1] **How quickly do different sized marble chips react?**
Search YouTube: The effect of surface area and particle size on the rate of a chemical reaction.

KEEN TO INVESTIGATE?

[2] **Can two solid substances react with each other?**
Search YouTube:
Lead Nitrate and Potassium Iodide Chemistry Demo Lab

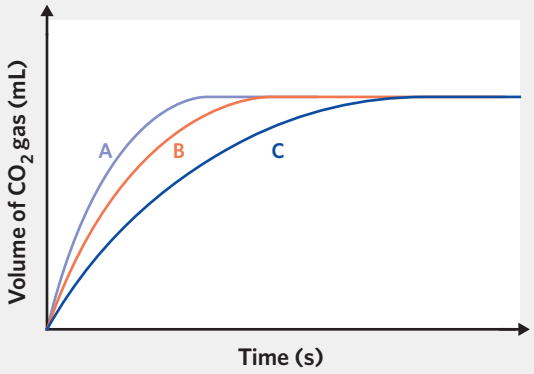
MISCONCEPTION

'The surface area of substances is always measurable.'

Realistically, the surface area of a reactant often can't be measured in a laboratory setting. Varying levels of surface area are simply categorised by the size and shape of the reactant particles i.e. lumps, chunks, powder etc.

WORKED EXAMPLE 2

The diagram provided is a volume versus time graph showing the volume of carbon dioxide produced from reactions between 25 mL of hydrochloric acid solution and 1 g samples of solid calcium carbonate of various sizes.



Determine which of the curves A, B, and C correspond to the reactions using large calcium carbonate chunks, small calcium carbonate chunks and calcium carbonate powder.

What information is presented in the question?

Three volume versus time graphs corresponding to three respective calcium carbonate sample types.

The reactions each involve the same volume of hydrochloric acid and the same mass of solid calcium carbonate.

What is the question asking us to do?

Match the curves to the sizes of the calcium carbonate samples.

Continues →

What strategies do we need in order to answer the question?

1. Recognise the link between the size of the particles in a sample and available surface area for collisions.
2. Recall how reaction rate changes as surface area of reactants changes.
3. Use the effect on reaction rate to match the curves to the samples.

Answer

As the size of the reactant particles in a sample decreases, there is more overall available surface area for collisions to occur. Therefore, more collisions will occur over a given period of time as the size of the reactant particles decreases, and thus, more successful collisions will occur, in turn increasing the reaction rate.

Looking at curve A, we can see this reaction reaches completion fastest (flattens out), and is therefore the curve for the reaction using the calcium carbonate powder.

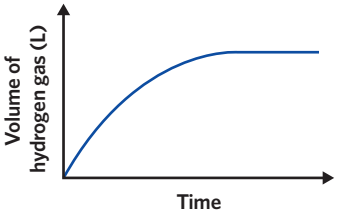
The reaction represented by curve B reaches completion more quickly than C, but still slower than A, and is therefore the curve for the reaction using the small calcium carbonate chunks.

Hence, curve C represents the slowest reaction, which is the reaction using the large calcium carbonate chunks.

PROGRESS QUESTIONS

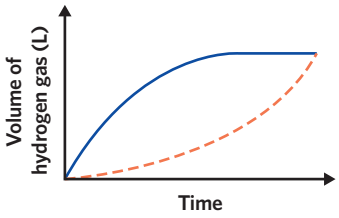
Question 4

A 2.0 g piece of magnesium ribbon was added to a known volume of 2.0 M hydrochloric acid. The volume of hydrogen gas produced during the reaction was measured and recorded. The graph below shows the result of this experiment.

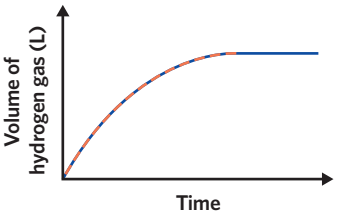


In a second experiment, 2.0 g of magnesium powder was added to the same volume of 2.0 M hydrochloric acid as used in the first experiment. Which of the following shows the expected graph of volume of hydrogen against time for the second experiment?

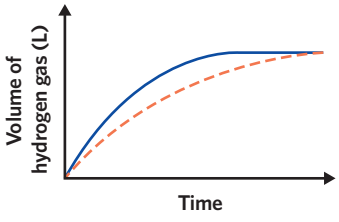
A.



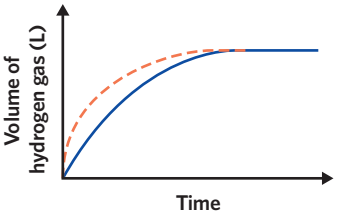
B.



C.



D.



Adapted from VCAA 2008 Exam 2 Short answer Q1b

Effect of pressure on reaction rate & effect of concentration on reaction rate 3.2.1.4 & 3.2.1.5

The number of reactant particles per unit of volume in a vessel will affect the reaction rate.

How does pressure affect reaction rate?

In lesson 14A of the Unit 1 & 2 Edrolo chemistry textbook, we learned about the relationship between temperature, volume and pressure of systems involving gases through the universal gas equation, $PV = nRT$. From this equation, we can see that pressure and volume are inversely proportional. This means that when the pressure of a vessel doubles, the volume halves, and when the pressure of a vessel halves, the volume doubles (figure 3).

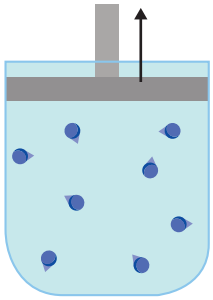
A decrease in volume means particles are in a smaller space, resulting in an increase in the number of reactant particles present per unit volume. As a result, there is an increase in the frequency of collisions between particles (higher number of collisions per unit time), and in turn, an increase in the frequency of successful collisions (higher number of successful collisions per unit time), thereby increasing the rate of reaction.

What happens to the reaction rate if more gas particles are added to the system?

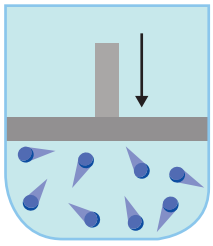
In the case of gases, if the volume and temperature are both kept constant and more moles of reactant have been injected into the system, the pressure will change. As we have explored earlier in this lesson, when more molecules are present in the same volume, there are more collisions, and so the rate of the reaction is increased.

How does concentration affect reaction rate?

The effect of reactant concentration on reaction rate is similar to the effect of pressure. When the concentration of a reactant in a solution is increased, there are more reactant particles present in the system per unit volume. Therefore, the collision frequency (and hence the number of successful collisions in a given amount of time) increases, in turn increasing the rate of the reaction.



Pulling up increases the volume and decreases the pressure and concentration



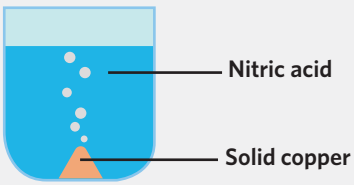
Pushing down decreases the volume and increases the pressure and concentration

Figure 3 The effect of changing volume on pressure and concentration

WORKED EXAMPLE 3

The equation and a diagram for the reaction between solid copper and nitric acid solution are given.

$Cu(s) + 4HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2NO_2(g) + 2H_2O(l)$



Which one of the following will **not** increase the rate of the above reaction?

A. Decreasing the size of the solid copper particles

B. Increasing the temperature of HNO_3 by 20 °C

C. Increasing the concentration of HNO_3

D. Allowing NO_2 gas to escape

What information is presented in the question?

The equation and a diagram for the reaction between solid copper and nitric acid solution.

What is the question asking us to do?

Determine which of the options will not result in an increased reaction rate.

What strategies do we need in order to answer the question?

1. Recall the factors that affect reaction rate.
2. Evaluate each option based on these factors.

Answer

Option A: decreasing the size of the solid copper particles will provide more surface area for reactant particles to collide. Hence, more frequent collisions will occur, and as a result, more successful collisions will occur, thereby increasing the reaction rate, so we can rule out option A.

Option B: increasing the temperature of the nitric acid will result in increased average kinetic energy of reactant particles, meaning more particles will collide with sufficient energy to break the bonds within the reactants. Hence, there will be a higher proportion of successful collisions, and in turn a faster reaction rate, so we can rule out option B.

Option C: increasing the concentration of nitric acid will lead to more reactant particles per unit of volume, and thus, more frequent collisions. This will cause an increase in the frequency of successful collisions, meaning the reaction rate will increase, so we can rule out option C.

Option D: allowing NO_2 gas to escape from the reaction vessel will decrease the pressure within the vessel, meaning there are fewer reactant particles per unit of volume and thus, less frequent collisions. This results in less frequent successful collisions, so only option D will not increase the reaction rate.

VCAA 2013 exam Multiple choice Q14

MISCONCEPTION

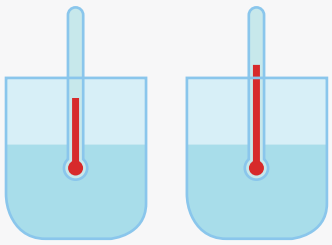
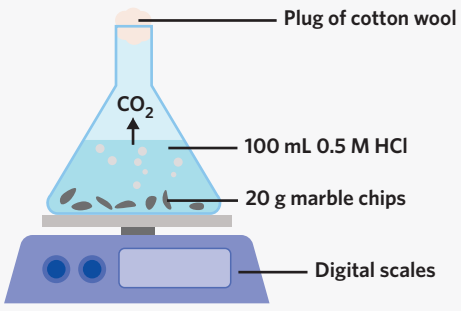
'In collision theory, frequency and proportion are the same.'

Frequency refers to the number of collisions that occur per unit time, whilst proportion refers to the number of those collisions that result in a reaction; that is, the number of those collisions that are successful.

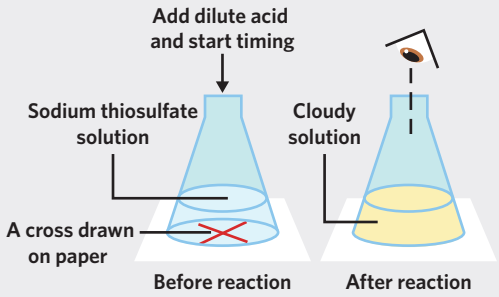
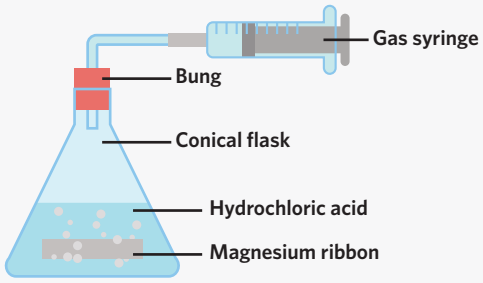
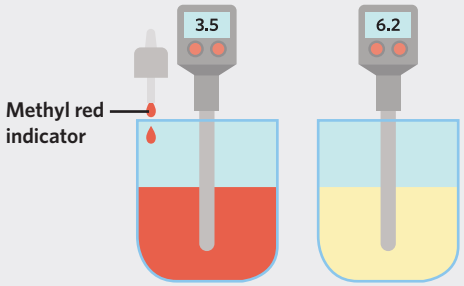
How can we measure reaction rates?

The speed at which a reaction proceeds can be measured in a number of ways, typically by observing a change in temperature, pH, mass, or colour, among others. Many of these measurement techniques are carried out in **open systems**, meaning any gas evolved during the reaction is allowed to escape. Some techniques however, such as the use of a gas syringe to measure the volume of gas evolved from a reaction, are carried out in **closed systems**, meaning the reaction vessel is airtight so no gas can enter or escape. Table 1 outlines common techniques and associated apparatus that are used to measure reaction rates.

Table 1 Common techniques used to measure reaction rates

Observation	Method	Diagram
Temperature	Thermometer: for reactions involving changes in heat energy, the reaction rate can be observed by timing how long it takes a system to reach a certain temperature. System: open Data: quantitative	
Change in mass due to solid formation or gas evolved	Balance: some reaction systems will demonstrate a change in mass due to the formation of a solid or an escaping gas. System: open Data: quantitative	

Continues →

Precipitate formation or colour change	Visual: reaction systems can be monitored subjectively for formation of precipitates or changes in colour. System: open Data: qualitative	
Volume of gas evolved	Gas syringe: the volume of gas evolved in a reaction system can be measured using a gas syringe fed into a reaction vessel through an air-tight bung. System: closed Data: quantitative	
pH	Indicator: the pH of a reaction system can be measured using a number of artificial and natural indicators. OR pH probe: the pH of a reaction system can also be measured using a pH probe. System: open Data: both qualitative and quantitative	

PROGRESS QUESTIONS

Question 5

Pieces of polished magnesium, Mg(s), are added to 100 mL of 1.0 M hydrochloric acid, HCl(aq), and react according to the equation below.

$Mg(s) + 2HCl(aq) \rightarrow H_2(g) + MgCl_2(aq)$

Which one of the following is most likely to decrease the rate of the reaction?

A. Use 100 mL of 2.0 M HCl.

B. Use Mg powder instead of Mg pieces.

C. Warm the 100 mL of 1.0 M HCl before using it.

D. Use unpolished Mg pieces instead of polished Mg pieces.

VCAA (NHT) 2022 exam Multiple choice Q2

Question 6

The factors which influence the rate of reaction between dilute hydrochloric acid and powdered calcium carbonate were investigated.

Which one of the following changes would **not** increase the rate of the reaction?

A. Stirring the mixture

B. Heating the reaction mixture

C. Increasing the concentration of the acid

D. Replacing the powder with a lump of calcium carbonate

VCAA 2010 Exam 2 Multiple choice Q1

Theory summary

- Requirements for a successful collision:
  1. Reactants must physically collide with each other.
  2. Reactants must collide with sufficient energy to break the bonds within them.
  3. Reactants must collide with the correct orientation for bonds to actually break.
- Summary of the factors affecting the rate of reaction:

Factor	Effect on particles	Effect on rate of reaction
Temperature ↑	Increases proportion of particles with sufficient energy to react, increases frequency of collisions	Increases rate of reaction
Surface area ↑	Increases frequency of collisions	Increases rate of reaction
Pressure ↑	Increases frequency of collisions	Increases rate of reaction
Concentration ↑	Increases frequency of collisions	Increases rate of reaction

4A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed

Use the following information to answer questions 7–9.

Carbon monoxide and hydrogen can be produced from the reaction of methane with water vapour according to the equation

$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \quad \Delta H = +206\ kJ$

Some methane and steam are placed in a closed container and allowed to react at a fixed temperature.

Question 7 🌶 (1 MARK)

Which of the following changes would be most likely to increase the rate of this reaction?

A. Increasing the amount of $CH_4(g)$ available to react

B. Decreasing the amount of $H_2O(g)$ available to react

C. Decreasing the temperature

D. Removing the lid from the closed container

Question 8 🌶 (1 MARK)

If 3 moles of $CH_4(g)$ were allowed to react with excess steam, how many moles of gas would be produced?

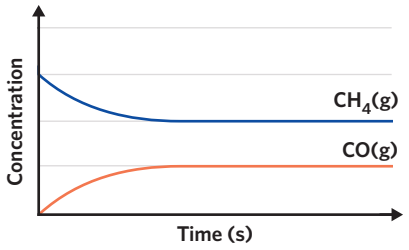
A. 2 **B.** 4 **C.** 6 **D.** 12

Question 9 🌶🌶 (2 MARKS)

The following graph shows the change in concentration of methane and carbon monoxide as the reaction progresses.

On a graph similar to the one provided, draw a line to show the change in concentration of hydrogen gas as the reaction progresses. Label this line, ensuring to account for mole ratios.

Adapted from VCAA 2007 Exam 1 Short answer Q1a



Exam-style

Question 10 (1 MARK)

A single 10 g piece of iron metal is completely submerged in 50 mL of 0.2 M nitric acid, HNO_3, contained in a 100 mL beaker. The experiment is performed at standard laboratory conditions (SLC). The reaction that occurs is

$$Fe(s) + 2HNO_3(aq) \rightarrow Fe(NO_3)_2(aq) + H_2(g)$$

The rate of the reaction would most likely increase if the

A. reaction was performed in a fume cupboard to remove the hydrogen gas formed.

B. single piece of iron metal was replaced with 70 pieces (0.1 g each) of iron metal.

C. volume of the acid was increased by adding 20 mL of water.

D. experiment was performed at 10 °C.

VCAA (NHT) 2021 exam Multiple choice Q5

Question 11 (3 MARKS)

The rates of chemical reactions may be explained using the collision theory model. Indicate whether the following statements about rates and the collision theory model are true or false.

I. Endothermic reactions are always slower than exothermic reactions.

II. All particles have the same kinetic energy at a fixed temperature.

III. Reactant particles need to collide with sufficient energy to react.

IV. The rate of a reaction at a constant temperature increases as the reaction proceeds.

V. Increasing the temperature increases the proportion of collisions with energy above the activation energy.

Adapted from VCAA 2007 Exam 1 Short answer Q1c

Question 12 (8 MARKS)

Hydrogen peroxide, H_2O_2, in aqueous solution at room temperature decomposes slowly and irreversibly to form water, H_2O, and oxygen, O_2, according to the following equation.

$$2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g) \quad \Delta H < 0$$

a. What effect will increasing the temperature have on the rate of O_2 production? Use collision theory to explain your answer. 3 MARKS

b. A solution of H_2O_2 is labelled '10 volume' because 1.00 L of this solution produces 10.0 L of O_2 measured at standard laboratory conditions (SLC) when the H_2O_2 in the solution is fully decomposed. Calculate the concentration of H_2O_2 in the '10 volume' solution, in grams per litre, when this solution is first prepared. 2 MARKS

c. Propose a method to determine how quickly a solution of H_2O_2 decomposes when stored at a particular temperature. 3 MARKS

Adapted from VCAA 2018 exam Short answer Q2a, c, d

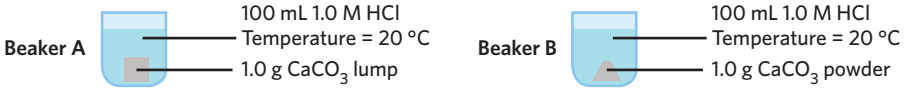
Question 13 (6 MARKS)

Two experiments were conducted to investigate various factors that affect the rate of reaction between calcium carbonate and dilute hydrochloric acid.

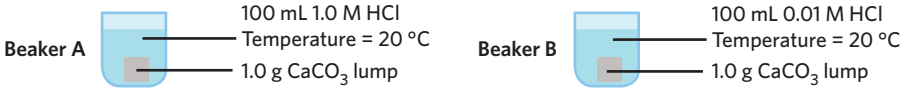
$$CaCO_3(s) + 2HCl(aq) \rightarrow CO_2(g) + CaCl_2(aq) + H_2O(l)$$

The two experiments are summarised in the diagrams below.

Experiment 1



Experiment 2



a. How could the rate of this reaction be measured in these experiments? 1 MARK

b. Identify the rate determining factor that is investigated in experiment 1. 1 MARK

c. In experiment 2, will the rate of reaction be faster in beaker A or beaker B? Explain your selection in terms of collision theory. 2 MARKS

d. Why is the following statement incorrect?
'Collision theory states that all collisions between reactant particles will result in a chemical reaction.' 2 MARKS

VCAA 2012 Exam 2 Short answer Q1

Question 14 🌶🌶🌶 (1 MARK)

5 mL of ethanol, CH_3CH_2OH, undergoes combustion in a test tube with a diameter of 1 cm. This experiment is performed in a fume cupboard. The temperature in the fume cupboard is 20 °C. Which one of the following actions will reduce the rate of reaction?

A. Mix 2 mL of a dilute solution of sodium hydroxide, NaOH, with the ethanol.

B. Perform the experiment in a test tube with a diameter of 2 cm.

C. Increase the temperature in the fume cupboard to 25 °C.

D. Increase the volume of the ethanol to 7 mL.

VCAA 2019 exam Multiple choice Q11

Key science skills

Question 15 🌶🌶🌶 (13 MARKS)

For his extended VCE chemistry experimental investigation project, Chris decided to investigate whether there is a relationship between the rate of the reaction between magnesium (Mg) and hydrochloric acid (HCl), and the concentration of the acid. The following is an extract from the scientific poster that Chris produced.

> **Question under investigation:** Is there a relationship between the rate of the reaction between magnesium, Mg, and different concentrations of hydrochloric acid, HCl?
>
> **Equation for the reaction:** $Mg(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$
> **Experimental design:** Four different concentrations of HCl were tested. The rate of each reaction was investigated by measuring the volume of hydrogen, H_2, gas produced at 60-second intervals.
>
> **Hypothesis:** The greater the concentration of the acid, the faster the reaction will be. I expect this because, for a reaction to occur, H^+ ions must collide with Mg atoms. The greater the concentration of the acid, the more frequently the H^+ ions will collide with the surface of the Mg and so the greater the amount of H_2 gas that will be produced.

a. In his hypothesis, does Chris demonstrate an understanding of the chemistry that is relevant to this experimental investigation? Explain your reasoning. 2 MARKS

b. In his poster, Chris outlined how the experimental investigation was conducted. An extract from his methodology is shown in the table below.

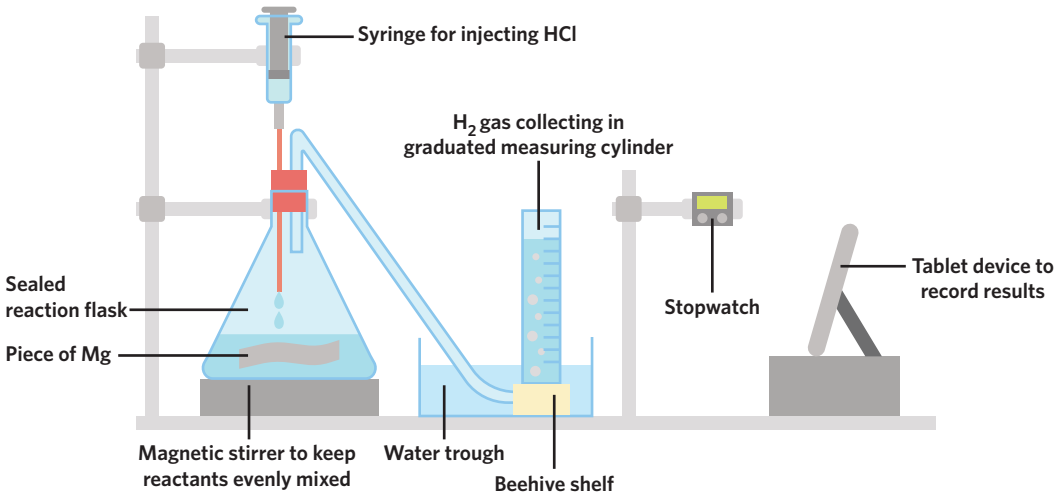
> **Methodology:** First, the variables were identified. The decisions I made are shown in Table 1.
>
> **Table 1** The variables identified

Variable	Classification	Details
Mass of Mg	Controlled variable	The first piece of Mg ribbon was weighed and measured, then the same length of Mg was used for each concentration of HCl tested.
Concentration of HCl	Dependent variable	0.5 M, 1.0 M, 1.5 M and 2.0 M solutions of HCl were tested.
Volume of HCl	Controlled variable	50.0 mL was used for each test, measured using a graduated measuring cylinder.

Is Chris's identification of the concentration of HCl as the dependent variable correct?
Give a reason for your answer. 1 MARK

c. Chris's poster included a diagram of the experimental set-up, supported by short notes, as shown below.

The experimental set-up:



Notes:

- Timing began the instant I started injecting the acid from the syringe above the flask onto the piece of Mg.
- The stopwatch was mounted next to the graduated measuring cylinder, and the volume and time were recorded using a video app on a tablet device and replayed in slow motion to allow the results to be obtained.
- The injection of 20.0 mL HCl into the sealed reaction flask immediately pushed 20.0 mL of air out of the flask and into the measuring cylinder. I recorded only the net volume of H_2 gas produced.

Identify one feature of Chris's experimental set-up and notes above that was designed to improve the accuracy of the results. Explain how this feature could improve accuracy. 2 MARKS

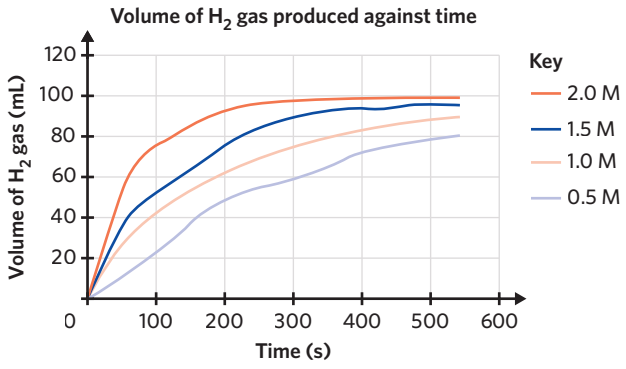
d. Chris also recorded his observations on his poster.

Observations: For the 2.0 M HCl, initially there was very rapid bubbling in the flask. The bubbling slowed over time. All Mg appeared to have dissolved. The flask became very hot. For the 1.5 M and 1.0 M HCl solutions, the bubbling was not as rapid as for the 2.0 M HCl, and for the 0.5 M HCl it was much slower. The solutions were still bubbling when timing stopped. The flasks became hot, although not as hot as the flask containing 2.0 M HCl.

Comment on Chris's observations, including the differences in the rate of bubbling and how well the experiment had been controlled. 3 MARKS

e. Chris replayed his video in slow motion, recorded his experimental results in his logbook and produced a graph for his poster. The graph is shown below.

Results:



What conclusions might Chris have stated, given his results for the question under investigation and his hypothesis? 2 MARKS

f. Suggest one other question Chris could ask to extend this experimental investigation and briefly outline an experimental design that would enable Chris to answer this question. You may present your answer as a list of main steps or as a simple flow chart. 3 MARKS

VCAA 2017 (Sample) exam Short answer Q10

FROM LESSONS 12B, 12C, 12D & 12E

Questions from multiple lessons

Question 16 (5 MARKS)

The decomposition of ammonia is represented by the following equation.

$2NH_3(g) \rightleftharpoons N_2(g) + 3H_2(g) \quad \Delta H = +92.4 \text{ kJ}$

a. The activation energy for the uncatalysed reaction is 335 kJ. The activation energy for the reaction when tungsten is used as a catalyst is 163 kJ. Draw a labelled energy profile diagram for the uncatalysed and catalysed reactions. 3 MARKS

b. When osmium is used as a catalyst, the activation energy is 197 kJ. Which catalyst – osmium or tungsten – will cause ammonia to decompose at a faster rate? Justify your answer in terms of the chemical principles you have studied this year. 2 MARKS

VCAA 2014 exam Short answer Q1

FROM LESSONS 1D & 2A

Question 17 (9 MARKS)

Adam is building a fishing boat and is looking for a material to use that experiences minimal rusting when in contact with water. To investigate which materials would be suitable, Adam exposes a range of different types of metal screws and nails to water and the air. He determines that iron nails react more quickly with oxygen from the air and water than those that are coated with a protective layer of zinc.

a. Explain why the iron nails coated with zinc rust more slowly than regular iron nails. 3 MARKS

b. A new set of iron nails are broken into smaller pieces and exposed to the same conditions. Would you expect rusting to occur faster or more slowly than the full sized nails?

Justify your answer. 3 MARKS

c. After construction, Adam tests the boat on the water. On the side of the boat exposed to the sun, it is observed that the nails rust much faster than those on the shaded side. Explain this observation, using collision theory to support your answer. 3 MARKS

FROM LESSONS 3A & 3C

Back to contents

4B Catalysts


Image: Sergey Nemirovsky/Shutterstock.com

Why do cars have honeycomb structures in their exhaust systems?

Catalytic converters are used to convert toxic gases released from a combustion engine into less toxic pollutants. In this lesson, we will learn about the effect of **catalysts** on the rate of reaction, and how we can represent this effect in energy profile diagrams.

KEY TERMS AND DEFINITIONS

Catalyst a substance used to provide an alternate reaction pathway with a lower activation energy, thus decreasing the amount of energy required to break the bonds in the reactants, meaning a greater proportion of reactant particles have sufficient energy to collide successfully

Heterogeneous catalyst a catalyst present in a different physical state from the reactants and products

Homogeneous catalyst a catalyst present in the same physical state as the reactants and products

Percentage yield efficiency of a chemical reaction that has taken place in terms of the amount of product actually produced compared to the predicted (theoretical) yield, which is given by $\frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

Reaction pathway a one or more chemical reactions designed to convert reactants into a desired product

STUDY DESIGN DOT POINTS

- factors affecting the frequency and success of reactant particle collisions and the rate of a chemical reaction in open and closed systems, including temperature, surface area, concentration, gas pressures, presence of a catalyst, activation energy and orientation
- the role of catalysts in increasing the rate of specific reactions, with reference to alternative reaction pathways of lower activation energies and represented using energy profile diagrams

4A → 4B

- 3.2.2.1 & 3.2.2.2 Function of catalysts & effect of catalysts on the reaction rate
- 3.2.2.3 Representing catalysed reactions

ESSENTIAL PRIOR KNOWLEDGE

1D Energy profile diagrams

4A Collision theory

See questions 33–34.

Function of catalysts & effect of catalysts on the reaction rate 3.2.2.1 & 3.2.2.2

Catalysts interact and bind with reactants to provide an alternate **reaction pathway** with a lower activation energy.

How do catalysts affect reaction rate?

In lesson 4A, we explored a number of factors that affect the rates of reactions; each of those factors involve changes either in the conditions of the reaction system, the reactant concentration, or size of the reactants.

USEFUL TIP

Green chemistry principle:
Catalysts should be selected to generate the same desired product(s) with less waste and using less energy and reagents in reaction processes/pathways. This will be covered in more detail in lesson 5D.

The use of catalysts is another method commonly used to increase the rate of a reaction. Catalysts provide an alternate reaction pathway with a lower activation energy by binding to reactants and decreasing the amount of energy required to break the bonds (figure 1). This allows a greater proportion of reactant particles to have the necessary activation energy to collide successfully. In turn, catalysts serve to increase the rates of reactions. However, since the function of catalysts lowers the activation energy for both the forward and reverse reactions, the **percentage yield** – the ratio of 'amount of product formed' to 'amount of product expected to form' – remains unchanged.

It's important to note that in catalysed reactions, the catalyst is not used up – it is chemically involved in a reaction, but not chemically altered. Catalysts can, however, be physically altered.[1]

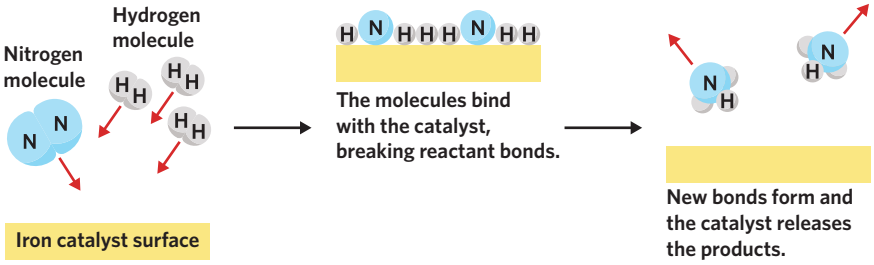


Figure 1 The use of an iron catalyst in the formation of ammonia

KEEN TO INVESTIGATE?

[1] **How does lead poison catalytic converters?**
Search: How Does Leaded Fuel Affect Catalytic Converters

USEFUL TIP

The word 'bind' covers electrostatic forces of attraction that are both reversible (temporary attraction) and irreversible (bond).

MISCONCEPTION

'The concentration of a catalyst in a reaction vessel changes throughout a reaction.'

Since catalysts are not used up in a reaction, they are present in consistent concentrations.

KEEN TO INVESTIGATE?

[2] **How does vanadium(V) pentoxide help produce sulfuric acid?**
Search YouTube: How to make Sulfuric Acid - Contact Process (4K)

USEFUL TIP

For now, you do not need to know how catalysts physically interact with reactants. In lesson 11B, we will investigate the mechanics of catalysts through biological catalysts called enzymes.

MISCONCEPTION

'Catalysts increase the percentage yield of reactions.'

Since catalysts speed up the forward and reverse reactions to the same extent, they do not increase the percentage yield of reactions – they only decrease the time required for all the products to form.

As we learned in lesson 4A, increasing the surface area available for collisions between reactant particles results in an increased reaction rate (according to collision theory). This principle should be considered when selecting an appropriate catalyst; in most cases, catalysts are used in porous or powdered forms. In figure 1, we can see the reaction between nitrogen and hydrogen molecules occurring on a solid iron catalyst. Industrially, the iron would actually be used in a powdered form to maximise the surface area of the catalyst.

Unlike enzymes (explored in lesson 11B) which are typically specific to certain reactants, chemical catalysts can often be used in multiple different reactions. Many of these chemical catalysts are either pure transition metals or transition metal compounds. For example, vanadium(V) pentoxide (V_2O_5) is used as a catalyst in the production of sulfuric acid from sulfur dioxide (the contact process[2]), the production of maleic anhydride from benzene, and several other processes.

USEFUL TIP

The effect of catalysts on a given reaction cannot be predicted. The utility of catalysts in specific reactions is based on trial and error.

MISCONCEPTION

'Catalysts increase the frequency of collisions.'

Since catalysts have no effect on the concentration of particles in a reaction vessel or how quickly those particles move, they do not affect the frequency of collisions, only the proportion of collisions that have the necessary activation energy to collide successfully.

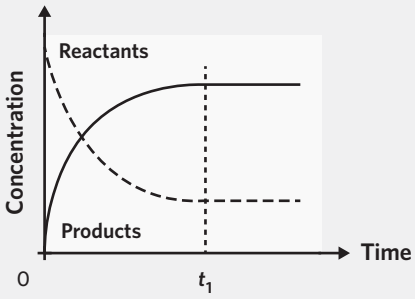
Catalysts are divided into two categories: **heterogeneous catalysts** and **homogeneous catalysts**. Heterogeneous catalysts are those present in a different physical state (or phase) to the reactants and products.[3] For example, in figure 1 solid iron catalyses the reaction between nitrogen and hydrogen gas to produce ammonia gas. Homogeneous catalysts, on the other hand, are those present in the same physical state as the reactants and products. We will explore homogeneous catalysis in lesson 8A when looking at esterification reactions, some of which are catalysed by sulfuric acid.

KEEN TO INVESTIGATE?

[3] **How does solid copper catalyse the oxidation of propanone (acetone)**
Search YouTube: Catalytic copper – heterogeneous catalysis demonstration

WORKED EXAMPLE 1

The concentration versus time graph for a reaction is shown below. This reaction takes place with a catalyst. The reaction reaches completion at time t_1.



The reaction is repeated without a catalyst. On a graph similar to the concentration versus time graph provided, sketch the expected curve for the products when the reaction is performed without a catalyst.

What information is presented in the question?

A concentration versus time graph for a catalysed reaction.

What is the question asking us to do?

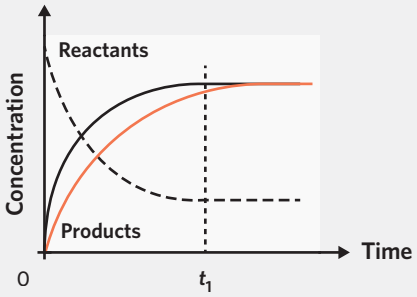
Sketch the curve for the concentration of the products in the uncatalysed reaction.

What strategies do we need in order to answer the question?

1. Recall the effect of a catalyst on reaction rate.
2. Recall the effect (if any) of a catalyst on the yield of a reaction.

Answer

Since a catalyst increases the reaction rate, the uncatalysed reaction would occur more slowly. Catalysts also have no effect on the yield of a reaction, and so the final concentration of the products should be the same.



Adapted from VCAA 2022 exam Short answer Q3c

As we learned in lesson 4A, experiments measuring the rate of a reaction can be carried out in open or closed systems. Whilst the general mechanism of a catalyst is the same in both open and closed systems, gas phase catalysts such as MnO_2 (used to catalyse the production of oxygen gas) are only suitable in closed systems where they cannot escape the reaction vessel.

PROGRESS QUESTIONS

Question 1

Which of the following statements about the use of catalysts in reversible reactions is correct?

A catalyst

A. decreases the activation energy of the forward reaction only.

B. increases the activation energy of the forward reaction only.

C. decreases the activation energy of the forward and reverse reactions.

D. increases the activation energy of the forward and reverse reactions.

Question 2

A catalyst for a reaction will

A. reduce the difference between the energy of the products and the energy of the reactants.

B. increase the proportion of successful collisions at a given temperature.

C. require an increase in temperature in order to work successfully.

D. only work for gaseous reactions.

VCAA (NHT) 2019 exam Multiple choice Q4

Representing catalysed reactions 3.2.2.3

Energy profile diagrams can be used to show the change in activation energy of catalysed reactions.

How can we represent catalysed reactions?

In lesson 1D, we explored enthalpy changes in combustion reactions using energy profile diagrams. We can use the same diagrams to represent the lower activation energy of alternate reaction pathways (figure 2).

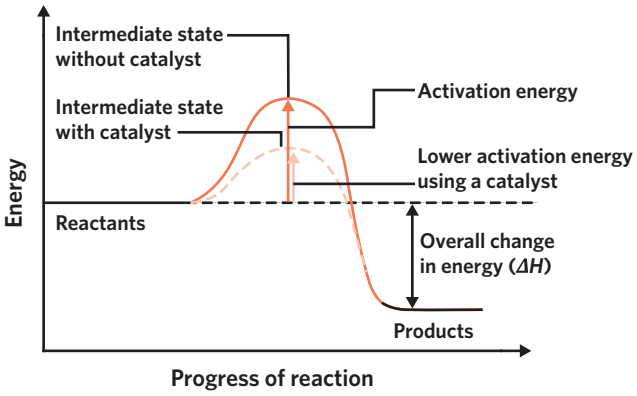


Figure 2 Energy profile diagram showing the activation energy of an uncatalysed and catalysed reaction

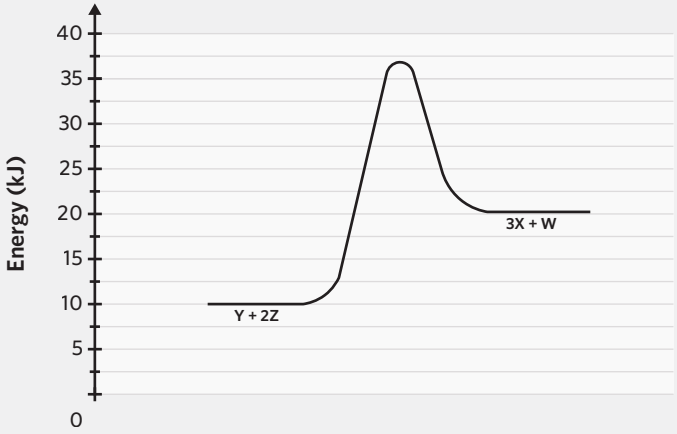
MISCONCEPTION

'A catalyst lowers the enthalpy change of a reaction.'

Catalysts have no effect on the overall change in energy of the reaction. They only lower the energy required for the reaction to occur.

WORKED EXAMPLE 2

Below is an energy profile diagram for an uncatalysed reversible reaction.



A catalyst was added to the system, causing the rate of the forward and reverse reactions to increase.

Which one of the following could be true for the catalysed reaction?

A. The activation energy to produce 1 mol of W is 29 kJ.

B. The activation energy to produce 1 mol of Z is 12 kJ.

C. The activation energy to produce 0.5 mol of X is 5 kJ.

D. The activation energy to produce 9 mol of Y is 120 kJ.

What information is presented in the question?

The energy profile diagram for an uncatalysed reversible reaction.

What is the question asking us to do?

Determine which of the options could be true if a catalyst were added to the reaction system.

What strategies do we need in order to answer the question?

1. Determine the activation energy for the forward reaction.
2. Determine the activation energy for the reverse reaction.
3. Recall our knowledge of mole ratios in combustion reactions.

Answer

For the forward reaction, $Y + 2Z \rightarrow 3X + W$, $E_a = 27$ kJ.

For the reverse reaction, $3X + W \rightarrow Y + 2Z$, $E_a = 17$ kJ.

Therefore, for the uncatalysed reaction, the activation energy to produce:

Option A: 1 mol of W is 27 kJ

Option B: 1 mol of Z is $\frac{17 \text{ kJ}}{2} = 8.5$ kJ

Option C: 0.5 mol of X is $0.5 \times \frac{27 \text{ kJ}}{3} = 4.5$ kJ

Option D: 9 mol of Y is $9 \times 17 \text{ kJ} = 153$ kJ

Since the activation energy is lower in the presence of a catalyst, the activation energy value in each option should be lower than the value calculated for the uncatalysed reaction.

Option A: $29 \text{ kJ} > 27 \text{ kJ}$

Option B: $12 \text{ kJ} > 8.5 \text{ kJ}$

Option C: $5 \text{ kJ} > 4.5 \text{ kJ}$

Option D: $120 \text{ kJ} < 153 \text{ kJ}$

Therefore, option D must be correct as it is the only option that proposes a lower activation energy than that of the uncatalysed reaction.

Adapted from VCAA (NHT) 2021 exam Multiple choice Q24

PROGRESS QUESTIONS

Question 3

Which of the following statements describes the effect of a catalyst on an energy profile diagram for an endothermic reaction?

A. The energy of the products will decrease.

B. The peak of the energy profile will increase in height.

C. The energy of the reactants will decrease.

D. The peak of the energy profile will decrease in height.

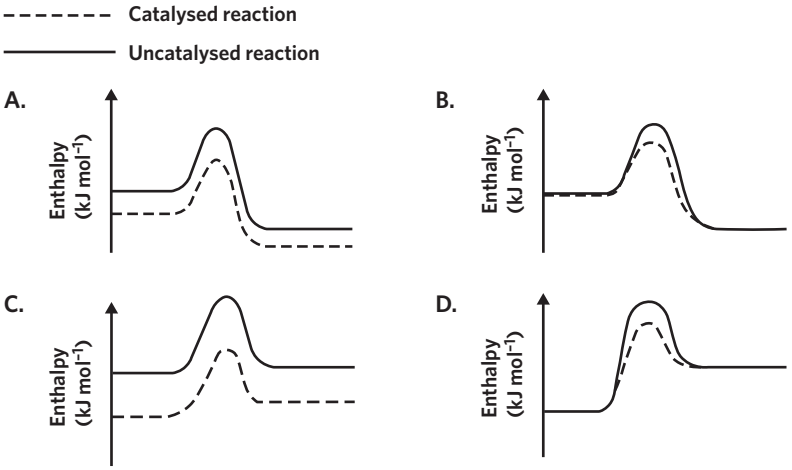
Continues →

Question 4

The oxidation of sulfur dioxide is an exothermic reaction. The reaction is catalysed by vanadium(V) oxide.

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$

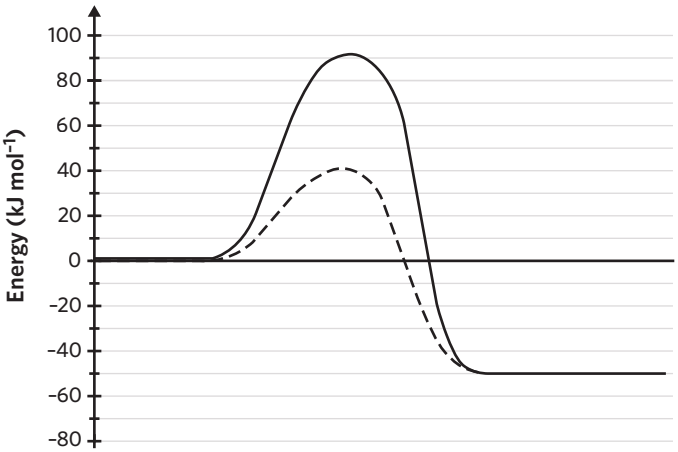
Which one of the following energy profile diagrams correctly represents both the catalysed and the uncatalysed reaction?



VCAA 2015 exam Multiple choice Q17

Question 5

The energy profile diagram below represents a particular reaction. One graph represents the uncatalysed reaction, and the other graph represents the catalysed reaction.



Which of the following **best** matches the energy profile diagram?

	E_a **uncatalysed reaction (kJ mol^{-1})**	ΔH **catalysed reaction (kJ mol^{-1})**
A.	40	−140
B.	90	−140
C.	40	−50
D.	90	−50

VCAA 2018 exam Multiple choice Q13

Theory summary

- Catalysts increase the reaction rate by creating an alternate reaction pathway with a lower activation energy, meaning a greater proportion of reactant particles have sufficient energy to collide successfully.
- Catalysts work by temporarily binding to reactants which decreases the amount of energy required to break the bonds in the reactants.
- Catalysts do not increase the percentage yield or yield of a chemical reaction, they increase the rate at which products are formed.
- Catalysts are not consumed in a reaction.
- Transition metals and their compounds are commonly used as catalysts in industrial processes.
- Energy profile diagrams are used to demonstrate the difference in activation energy for catalysed and uncatalysed reactions.

4B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 6–8.

NO(g) is produced in combustion engines such as a car engine. Platinum and palladium catalysts are used in the exhaust system to speed up the decomposition of NO(g) into $N_2(g)$ and $O_2(g)$.

$2NO(g) \rightleftharpoons N_2(g) + O_2(g) \quad \Delta H = -180.8$ kJ

Question 6 (1 MARK)

How many moles of gas are produced per mole of decomposed NO(g)?

A. 1

B. 2

C. 4

D. 8

Question 7 (1 MARK)

Which of the following is a likely effect of the use of platinum and palladium catalysts in the decomposition of NO(g)?

A. Decreased rate of $N_2(g)$ production

B. Increased rate of $O_2(g)$ production

C. Increased activation energy

D. Increased enthalpy change

Question 8 (3 MARKS)

Sketch a fully labelled energy profile diagram for the decomposition of NO(g). In your sketch, indicate the effect of using a catalyst in this reaction.

Adapted from VCAA 2011 Exam 2 Short answer Q5b

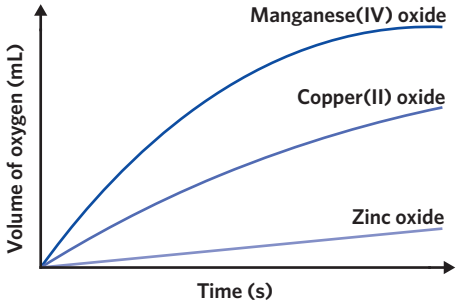
Exam-style

Question 9 (4 MARKS)

Different catalysts can be used for the same reaction, however, it is important to select the catalyst that generates the same desired product with less waste and using less energy and reagents in the reaction process. The decomposition of hydrogen peroxide can be catalysed by a variety of different catalysts.

$2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g)$

The graph provided shows the beginning stages of the decomposition of hydrogen peroxide using different compounds of transition metals as catalysts. Note: the graph does not represent the decomposition reaction going to completion.



a. Which of the three catalysts increases the rate of the decomposition of hydrogen peroxide the most? Justify your answer. 2 MARKS

b. Each of the catalysts represented in the graph often come in powdered form. Explain why compounds of transition metal catalysts are often used as powders rather than lumps. 2 MARKS

Key science skills

Question 10 (5 MARKS)

A student investigated the effect of different catalysts on the molar enthalpy of the decomposition reaction of hydrogen peroxide. The student's report is provided below.

Report – Effect of different catalysts on the enthalpy of a reaction

Background

Different catalysts, such as manganese(IV) dioxide, MnO_2, and iron(III) nitrate solution, $Fe(NO_3)_3$, will increase the rate of decomposition of hydrogen peroxide.

$2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g)$

Aim

To investigate the effect of using different catalysts on the molar enthalpy of the decomposition of hydrogen peroxide.

Procedure

The temperature change was measured when MnO_2 catalyst was added to a volume of hydrogen peroxide in a beaker until all hydrogen peroxide decomposed. The procedure was repeated using $Fe(NO_3)_3$ solution as a catalyst.

Results

	Trial 1	Trial 2
Volume H_2O_2	100 mL	200 mL
Concentration H_2O_2	2.0 M	4.0 M
Catalyst	0.5 g MnO_2	50 mL 0.1 M $Fe(NO_3)_3$
Temperature change (°C)	3.0	10.1

Conclusion

The change in temperature using the $Fe(NO_3)_3$ catalyst was greater than the change in temperature using the MnO_2 catalyst. This demonstrates that the molar enthalpy for the decomposition reaction depends on the catalyst used.

The student's conclusion is not valid because the experimental design is flawed. Critically review the student's experimental design. In your response, you should:

a. Identify **three** improvements or modifications that you would make to the experimental design. 3 MARKS

b. Had the experiment been valid, identify the expected conclusion that the student would draw. 1 MARK

c. Evaluate the conclusiveness of the results obtained. 1 MARK

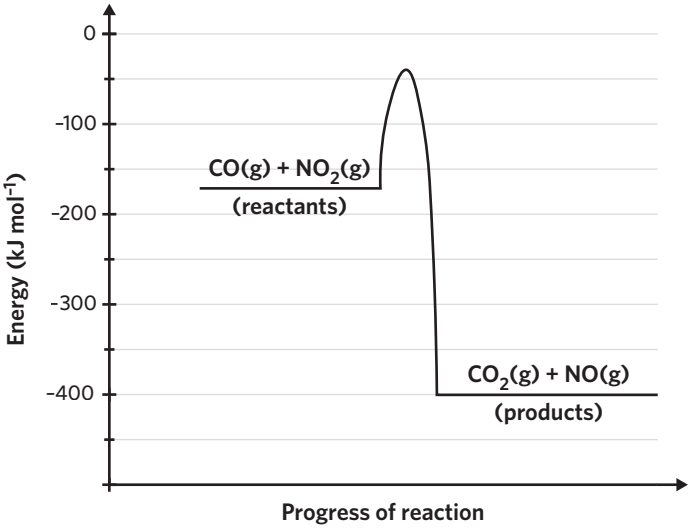
Adapted from VCAA 2014 exam Short answer Q12

FROM LESSONS 12B, 12D & 12E

Questions from multiple lessons

Question 11 (6 MARKS)

The graph below represents the energy changes over the course of a chemical reaction.



a. Give the magnitude and sign of ΔH for the forward reaction in kJ mol^{-1}. 1 MARK

b. Give the activation energy for the reverse reaction in kJ mol^{-1}. 1 MARK

c. A suitable catalyst is discovered for the reaction.

i. What would be the likely effect of the catalyst on the activation energy of this reaction? Explain your answer. 2 MARKS

ii. What would be the likely effect, if any, of the catalyst on the value of ΔH? Explain your answer. 2 MARKS

FROM LESSON 1D

Chapter 4 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

A catalyst

A. slows the rate of reaction.

B. has no effect on the rate of reaction.

C. ensures that a reaction is exothermic.

D. provides an alternative pathway for the reaction with a lower activation energy.

Adapted from VCAA 2017 exam Multiple choice Q1

Question 2 (1 MARK)

Using powdered reactants instead of larger chunks typically causes reactions to occur more quickly.
Which of the following **best** explains the effect of using powdered reactants on the rate of reaction?

A. There is a greater area for reactants to collide, meaning more reactants will collide successfully, thereby increasing the rate of reaction.

B. There is a greater area for reactants to collide, meaning collisions will occur more frequently, thereby increasing the chance of a successful collision which is likely to increase the rate of reaction.

C. There is a smaller area for reactants to collide, meaning more reactants will collide successfully, thereby increasing the chance of a successful collision which is likely to increase the rate of reaction.

D. There is a smaller area for reactants to collide, meaning collisions will occur more frequently, thereby increasing the rate of reaction.

Question 3 (1 MARK)

Which of the following statements is true?

A. Catalysts decrease the difference in enthalpy between reactants and products.

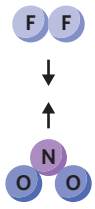
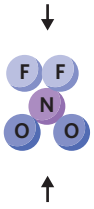
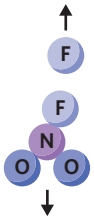
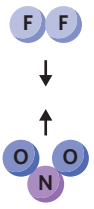
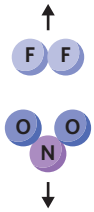
B. Catalysts are gradually used up in a reaction.

C. Catalysts increase the proportion of particles with sufficient energy to react.

D. Catalysts increase the yield of a reaction.

Question 4 (1 MARK)

In the diagram shown, one collision is successful, but the other is not. Which of the following factors explains the success of the first reaction?

Collision One			Collision Two		
Before Collision	**Collision**	**After Collision**	**Before Collision**	**Collision**	**After Collision**
					

A. Temperature

B. Concentration

C. Orientation

D. Catalysis

Use the following information to answer questions 5–6.

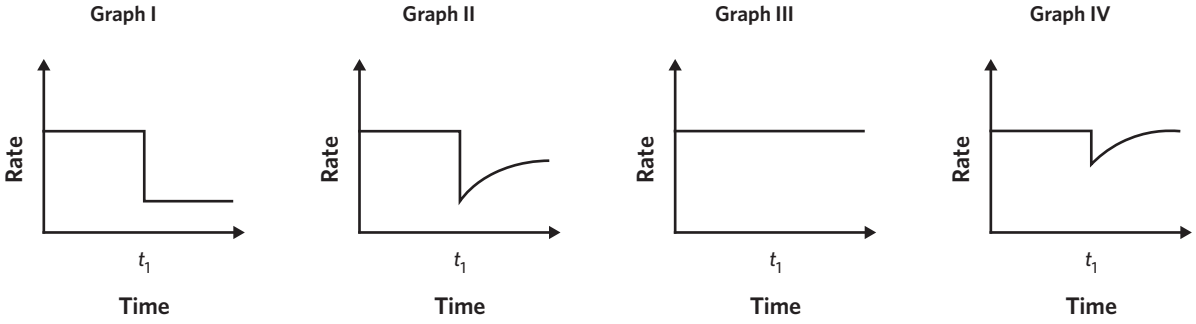
Reactants A and B are placed in a sealed container with a suitable catalyst where they react according to the following equation:

$A(g) + B(g) \rightleftharpoons C(g)$

Prior to time t_1, the system is in equilibrium (the concentrations of species are constant). A small amount of a compound is added to the container at time t_1. The compound 'poisons' the catalyst and stops it working, without being consumed.

Question 5 (1 MARK)

Which one of the graphs best represents the rate of the forward reaction versus time?

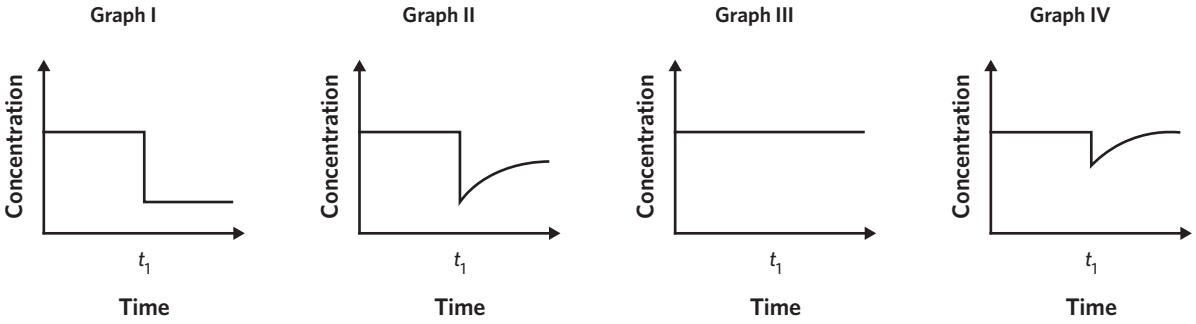


A. Graph I **B.** Graph II **C.** Graph III **D.** Graph IV

Adapted from VCAA 2010 Exam 2 Multiple choice Q4

Question 6 (1 MARK)

Which one of the graphs best represents the concentration of product C versus time?



A. Graph I **B.** Graph II **C.** Graph III **D.** Graph IV

Adapted from VCAA 2010 Exam 2 Multiple choice Q5

Question 7 (1 MARK)

Consider the following trials for the reaction between 2.0 g of magnesium ribbon and hydrochloric acid.

$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

Trial	Temperature (°C)	Concentration of HCl (M)
1	50	2.0
2	25	2.0
3	50	5.0

The order of the expected rates of reaction for each trial, from slowest to fastest, is

A. 1, 2, 3 **B.** 2, 1, 3 **C.** 3, 2, 1 **D.** 3, 1, 2

Question 8 (1 MARK)

The Ostwald process is used to convert ammonia into nitric acid. The first step in the process is the oxidation of ammonia in the presence of a platinum wire gauze catalyst to form nitrogen monoxide.

$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$

Which of the following would **not** increase the rate of this reaction?

A. Decreasing the volume of the reaction vessel

B. Increasing the pressure of the reaction vessel

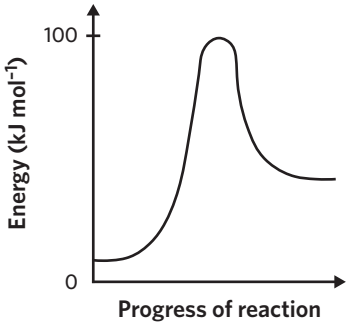
C. Increasing the temperature in the reaction vessel

D. Using a sheet of platinum instead of the platinum wire gauze

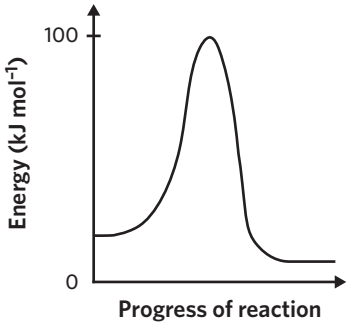
Question 9 (1 MARK)

Which of the energy profile diagrams most likely represents the fastest reaction at 25 °C and 100 kPa?

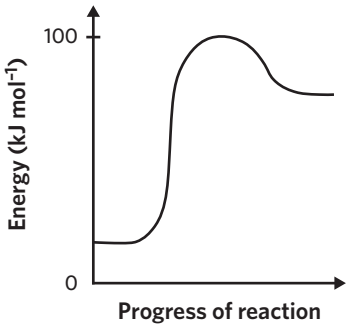
A.



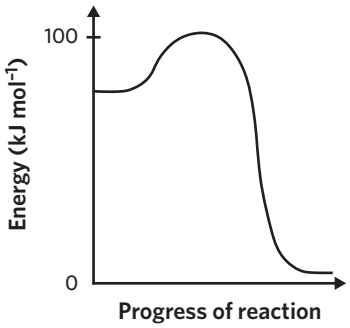
B.



C.

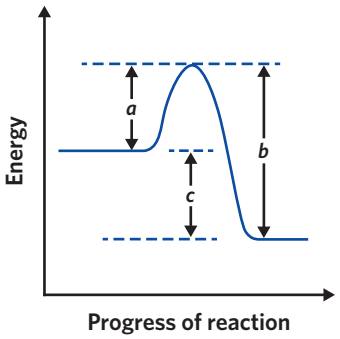


D.



Question 10 (1 MARK)

Consider the following energy profile for a particular chemical reaction, where *a*, *b* and *c* represent enthalpy changes during the reaction.



The following statements are made about the energy profile produced when a suitable catalyst has been added to the energy profile shown.

I. The activation energy for the forward reaction is less than $c - b$.

II. *b* represents the activation energy for the reverse reaction.

III. The activation energy for the forward reaction will be less than *a*.

Which of these statements are correct?

A. I only

B. III only

C. I and II

D. I and III

Short answer (30 MARKS)

Question 11 (4 MARKS)

Chemical reactions play a critical role in many industrial processes, and the rate of a chemical reaction can be influenced by several factors. Consider the reaction between hydrogen gas and iodine gas to produce hydrogen iodide gas.

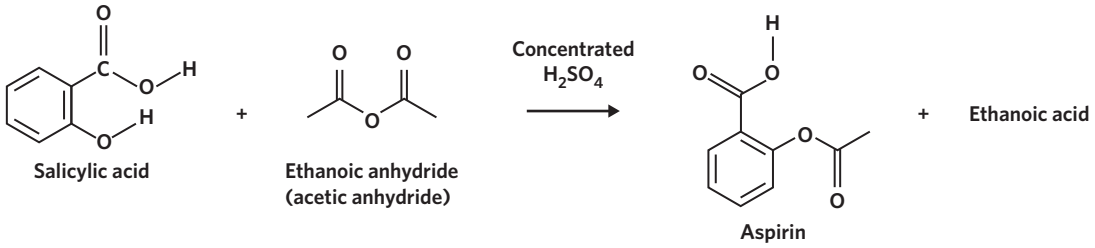
$H_2(g) + I_2(g) \rightarrow 2HI(g)$

a. Explain how the rate of this reaction would be affected by an increase in the concentration of hydrogen gas. 2 MARKS

b. If this reaction is carried out in a closed container at a constant temperature, explain how the rate of the reaction would be affected by an increase in the pressure of the system. 2 MARKS

Question 12 (4 MARKS)

A student mixed salicylic acid with acetic anhydride (ethanoic anhydride) in the presence of concentrated sulfuric acid. The products of this reaction were the painkilling drug aspirin (acetyl salicylic acid) and ethanoic acid.



Salicylic acid

Ethanoic anhydride (acetic anhydride)

Aspirin

Sulfuric acid is used as a catalyst in this reaction. Explain how a catalyst increases the rate of this reaction.

Adapted from VCAA 2015 exam Short answer Q5cii

Question 13 (12 MARKS)

The decomposition of gas X is an endothermic reaction resulting in the formation of gases Y and Z.

$X(g) \rightleftharpoons Y(g) + Z(g) \quad \Delta H = +40 \text{ kJ mol}^{-1}$

A scientist is attempting to measure the yield of gas Z from the decomposition of gas X.

a. Should the scientist conduct this investigation in an open or closed system? Justify your answer. 2 MARKS

b. Using collision theory, explain why the decomposition of X occurs more quickly at higher temperatures. 3 MARKS

c. To increase the yield of gas Z, the scientist proposes the use of an effective catalyst, W. Would the use of a catalyst affect the yield of gas Z? Explain your answer. 2 MARKS

d. The activation energy for the decomposition of X is +120 kJ mol^{-1}. In the presence of catalyst W, the activation energy is only +90 kJ mol^{-1}.

i. Define the term activation energy. 1 MARK

ii. Draw a fully labelled energy profile diagram for both the catalysed and uncatalysed decomposition of X. 3 MARKS

iii. Using either your energy profile diagram or the information provided in the question, what is the activation energy for the catalysed reverse reaction? 1 MARK

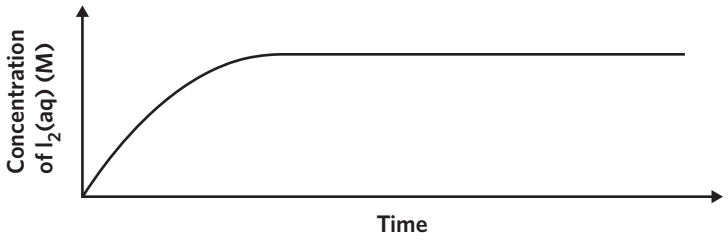
Question 14 (4 MARKS)

Peroxydisulfate ions can react with iodide ions in solution to form sulfate ions and aqueous iodine.

$S_2O_8^{2-}(aq) + 2I^-(aq) \rightarrow 2SO_4^{2-}(aq) + I_2(aq)$

a. This reaction can be catalysed by an iron(II) or an iron(III) salt. Using the charges of ions, explain why these two compounds are suitable catalysts. 2 MARKS

b. The following graph shows the concentration of $I_2(aq)$ in a reaction vessel over time.



On a graph similar to the one shown, draw the graph of the concentration of $I_2(aq)$ over time when an iron(III) salt catalyst is used. 2 MARKS

Question 15 (6 MARKS)

The Contact Process is an important industrial process for the production of sulfuric acid. The process involves several reactions, including the oxidation of sulfur dioxide to sulfur trioxide, which is then used to produce sulfuric acid. The equation for the oxidation of sulfur dioxide is given.

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$

a. Identify two conditions that could be implemented to increase the rate of sulfur dioxide oxidation. 2 MARKS

b. The oxidation of sulfur dioxide occurs in the presence of vanadium(V) pentoxide. State and explain the probable role of vanadium(V) pentoxide in this step of the Contact Process, and the benefit this has in industry. 3 MARKS

c. The Contact Process is not the only process that uses a compound of vanadium to catalyse reactions; vanadium catalysts are used in rubber synthesis, petroleum cracking and the synthesis of some high-molecular compounds. Identify the feature of vanadium that makes it a suitable catalyst in several industrial processes. 1 MARK

Key science skills (10 MARKS)

Question 16 (10 MARKS)

Catalytic converters are used in combustion engines to remove the toxic gases nitrogen monoxide and carbon monoxide that are produced from the combustion of petrol. They are constructed using a ceramic honeycomb structure coated with a mixture of precious metals such as platinum.

a. Why do catalytic converters use a honeycomb structure? 2 MARKS

b. Identify and explain one key economic concern associated with the design of catalytic converters. 2 MARKS

c. Catalytic converters can be 'poisoned' if the wrong fuel is used. A notable contaminant of catalytic converters is lead found in the exhaust of leaded fuels. As a result, cars with catalytic converters can only be run on unleaded fuels.

i. Explain how leaded petrol 'poisons' a catalytic converter. 2 MARKS

ii. Identify and explain two key environmental concerns associated with the 'poisoning' of catalytic converters. 4 MARKS

FROM LESSON 12B

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5

CHAPTER 5

Extent of chemical reactions

LESSONS

5A Equilibrium reactions

5B Calculating equilibrium constants

5C Changes to equilibrium

5D Compromise conditions

Chapter 5 review

KEY KNOWLEDGE

- the distinction between reversible and irreversible reactions, and between rate and extent of a reaction
- the dynamic nature of homogenous equilibria involving aqueous solutions or gases, and their representation by balanced chemical or thermochemical equations (including states) and by concentration-time graphs
- the change in position of equilibrium that can occur when changes in temperature or species or volume (concentration or pressure) are applied to a system at equilibrium, and the representation of these changes using concentration-time graphs
- the application of Le Chatelier's principle to identify factors that favour the yield of a chemical reaction
- calculations involving equilibrium expressions (including units) for a closed homogeneous equilibrium system and the dependence of the equilibrium constant (K) value on the system temperature and the equation used to represent the reaction
- the reaction quotient (Q) as a quantitative measure of the extent of a chemical reaction: that is, the relative amounts of products and reactants present during a reaction at a given point in time
- responses to the conflict between optimal rate and temperature considerations in producing equilibrium reaction products, with reference to the green chemistry principles of catalysis and designing for energy efficiency

Image: Rattiya Thongdumhyu/Shutterstock.com

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5A Equilibrium reactions

STUDY DESIGN DOT POINTS

- the distinction between reversible and irreversible reactions, and between rate and extent of a reaction
- the dynamic nature of homogenous equilibria involving aqueous solutions or gases, and their representation by balanced chemical or thermochemical equations (including states) and by concentration-time graphs

5A 5B 5C 5D

- 3.2.3.1 Reversible and irreversible reactions
- 3.2.3.2 Rate vs extent of reaction
- 3.2.4.1 Dynamic equilibrium
- 3.2.4.2 Representing equilibrium reactions

ESSENTIAL PRIOR KNOWLEDGE

- 1D Combustion reactions
- 2A Stoichiometric ratios
- 4A Rate of reaction

See questions 35–37.



Image: GreenArt/Shutterstock.com

Can we 'unbake' a cake back into its ingredients?

Baking a cake involves **irreversible reactions**, meaning we cannot extract the original ingredients used to bake it. In this lesson, we will explore the reversibility of reactions, as well as the distinction between rate and **extent** of reactions. We will also investigate **equilibrium reactions**, a type of **reversible reaction** in which products and reactants are constantly being created and broken down.

KEY TERMS AND DEFINITIONS

Concentration-time graph a graph of concentration versus time used to represent equilibrium reactions

Dynamic equilibrium the point in a reversible chemical reaction when the rate of the forward reaction is equal to the rate of the reverse reaction, and the concentrations of products and reactants are constant

Equilibrium reaction reaction in which reactants and products are constantly being formed

Extent the proportion of reactants that have been converted into products

Irreversible reaction a reaction that can only proceed in one direction and cannot be reversed

Rate-time graph a graph of rate of reaction versus time used to represent equilibrium reactions

Reversible reaction a reaction that can proceed both forwards and backwards

Theoretical yield the expected amount of product formed based on stoichiometric ratios and the mass of limiting reactant used

Yield the mass of product obtained during a chemical reaction

Reversible and irreversible reactions 3.2.3.1

Chemical reactions can be classified as either reversible or irreversible based on whether the products formed can be readily converted back to reactants.

What is the distinction between reversible and irreversible reactions?

An irreversible reaction is a reaction that can only proceed in one direction and cannot be reversed. That is, once the reactants are converted into products, they cannot be converted back into reactants. Common examples of irreversible reactions include combustion reactions, such as the combustion of methane (figure 1). The equations for irreversible reactions are written with the unidirectional arrow (→) to indicate that the reaction proceeds in one direction only, such as in the equation for the combustion of methane given in figure 1.

On the other hand, a reversible reaction is a reaction that can proceed both forwards and backwards to a considerable extent. Therefore, once the products of a reversible reaction are formed, they can react to reform the reactants. A famous example of a reversible reaction is the production of ammonia from nitrogen gas and hydrogen gas, called the 'Haber-Bosch process'.[1]

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

As shown above, equations for reversible reactions are written with bidirectional 'harpoon' arrows (⇌) to indicate that the reaction can proceed in either the forwards or backwards direction. In reversible reactions, there is always some amount of products and some amount of reactants present in the reaction system. Therefore, we say that reversible reactions do not reach 'completion'.

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$



Image: ggw/Shutterstock.com

Figure 1 The combustion of methane as a fuel source for a Bunsen burner is an irreversible reaction.

USEFUL TIP

Equilibrium reactions are a type of reversible reaction in which the amounts of products and reactants reach a constant concentration. In a closed system, any reversible reaction will reach equilibrium.

KEEN TO INVESTIGATE?

[1] **Why is the Haber-Bosch process so important?**
Search YouTube: The chemical reaction that feeds the world

PROGRESS QUESTIONS

Question 1

Which of the following is a characteristic of reversible reactions?

A. They can only proceed in one direction.
B. They can proceed to completion.
C. They can reach equilibrium.
D. None of the above

Question 2

Which of the following is an example of an irreversible reaction?

A. The combustion of methane
B. The decomposition of calcium carbonate in a closed system
C. The formation of a metal oxide from a metal and oxygen
D. The breakdown of water into hydrogen and oxygen using electricity

Question 3

Which of the following equations represents an irreversible reaction?

A. $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$
B. $C_8H_{18}(l) + 12\frac{1}{2}O_2(g) \rightarrow 8CO_2(g) + 9H_2O(l)$
C. $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$
D. $N_2O_4(g) \rightleftharpoons 2NO_2(g)$

Rate vs extent of reaction 3.2.3.2

When analysing a chemical reaction, it is important to consider both the rate at which the reaction proceeds, and the extent to which the reaction proceeds.

What is the distinction between the rate and extent of a reaction?

The rate of a reaction refers to how much product is formed over a given period of time. As we learned in lessons 4A and 4B, this can be influenced by factors such as temperature, concentration, pressure, and the use of catalysts. The extent of a reaction, however, refers to the proportion of reactants that have been converted into products. In lesson 5C, we will explore the factors that can influence the extent of a reaction. While the rate of a reaction is important for understanding the kinetics of a reaction and the factors that influence it, the extent of a reaction is important for understanding the **yield** of a reaction.

USEFUL TIP

The yield of products for a reversible reaction is never equivalent to the theoretical yield – some amount of the reactants always remains unreacted.

The yield of a reaction refers to the amount of product that is obtained in a chemical reaction. It is typically expressed as a percentage yield, a percentage of the **theoretical yield** (the yield that should theoretically be produced based on stoichiometric ratios). The concept of percentage yield will be explored in greater detail in lesson 8B.

$$\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

In lesson 5B, we will investigate the equilibrium constant (K). The equilibrium constant is the ratio of the concentrations of the products to the concentrations of the reactants in a reaction. The magnitude of K can be used to indicate the extent of a reaction (figure 2). For large K values ($> 10^4$), we can assume that the reaction has proceeded to a considerable extent, meaning there is a significant concentration of product in the reaction system. For K values between 10^4 and 10^{-4}, we can assume that the reaction has proceeded to a moderate extent and that considerable concentrations of both products and reactants are present in the reaction system. For small K values ($< 10^{-4}$), we can assume that the reaction has not proceeded to any considerable extent, and that there is a considerable proportion of reactants present.

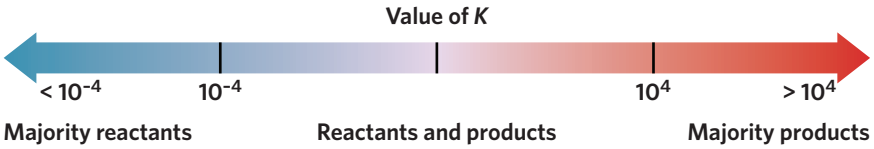


Figure 2 The magnitude of K indicates the ratio of reactants to products present at equilibrium.

PROGRESS QUESTIONS

Question 4

Which of the following is **not** a measure of the extent of a reaction?

A. The change in concentration of reactants over time

B. The change in concentration of products over time

C. The change in mass of the reactants over time

D. The total number of reactant molecules

Continues →

Question 5

Which of the following statements is true regarding the relationship between rate and extent of a reaction?

A. The rate and extent of a reaction are independent of each other.

B. A slow reaction will always have a low extent.

C. A fast reaction will always have a high extent.

D. A fast reaction will always have a low extent.

Question 6

Which of the following statements best describes the extent of a chemical reaction?

A. It is the amount of product obtained in a reaction.

B. It is the amount of reactant obtained in a reaction.

C. It is the proportion of products that have formed reactants.

D. It is the proportion of reactants that have formed products.

Question 7

If a chemical reaction has a theoretical yield of 50 grams and an actual yield of 40 grams, what is the percentage yield?

A. 40%

B. 50%

C. 80%

D. 125%

Question 8

The equilibrium constant, K, is a measure of what aspect of a chemical reaction?

A. The rate of the reaction

B. The yield of the reaction

C. The extent of the reaction

D. The activation energy of the reaction

Dynamic equilibrium 3.2.4.1

In reversible reaction systems, a state is reached in which the concentrations of products and reactants remain constant.

How can the amounts of products and reactants remain constant in a chemical reaction?

So far, we have learned that reversible reactions are those in which the products formed can react with each other to reform the reactants. In closed systems, reversible reactions reach a state known as **dynamic equilibrium**; in this state, the rate of the forward reaction is equal to the rate of the reverse reaction. Therefore, reactants and products are produced at the same rate, meaning there is no net change in the concentration of the products or reactants. However, it is important to note that when a system is in dynamic equilibrium both the forward and reverse reactions are still occurring.

MISCONCEPTION

'All reactions reach dynamic equilibrium.'

For a reaction to reach equilibrium, it must be able to proceed in both the forward and reverse directions. Therefore, only reversible reactions are able to reach dynamic equilibrium.

Since there is no net change in the concentration of the products or reactants, for a system in equilibrium:

- The amounts of reactants and products are constant.
- The temperature of the system is constant (heat is being absorbed at the same rate it is being released).
- The pressure of the system is constant (the number of gas particles is constant).

MISCONCEPTION

'The amounts of products and reactants are always equal in dynamic equilibrium.'

When a system reaches dynamic equilibrium, the rates of the forward and reverse reactions are equal and the concentrations of the reactants and products remain constant (but not necessarily equal).

USEFUL TIP

In VCE chemistry, we will only explore homogeneous equilibria. That is, equilibria in which the products and reactants are present in the same phase or state.

PROGRESS QUESTIONS

Question 9

In a dynamic equilibrium system, which of the following is true?

A. The forward reaction rate is faster than the reverse reaction rate.

B. The reverse reaction rate is faster than the forward reaction rate.

C. The forward reaction rate is equal to the reverse reaction rate.

D. The forward and reverse reactions have stopped completely.

Question 10

Which of the following is **not** true for a system in dynamic equilibrium?

A. Reactants are constantly being formed.

B. The temperature steadily increases over time.

C. The total gas pressure of the system is constant.

D. The rate of the forward reaction is equal to the rate of the backward reaction.

Representing equilibrium reactions 3.2.4.2

A system reaching equilibrium can be represented by both **concentration-time graphs** and **rate-time graphs**.

How are concentration-time graphs used to represent equilibrium reactions?

When we investigate equilibrium reactions, we are typically observing the changes in the concentrations of products and reactants over time. We can represent these changes using concentration-time graphs, such as the one shown in figure 3.

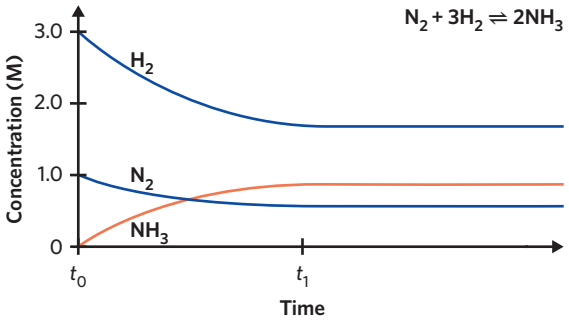


Figure 3 Concentration-time graph for the formation of ammonia from nitrogen and hydrogen gas

In figure 3, we can see that at time t_0, the concentrations of H_2, N_2 and NH_3 are 3.0 M, 1.0 M, and 0.0 M respectively. This tells us that hydrogen gas and nitrogen gas were added to a reaction vessel and allowed to react, forming ammonia. We can see that the concentrations of H_2 and N_2 initially decrease, whilst the concentration of ammonia increases. This is expected as H_2 and N_2 react to form NH_3.

We know that the reaction represented by figure 3 is an equilibrium reaction because the concentrations of all species present eventually plateau as the rates of the forward and reverse reactions become equal. The time at which the concentrations plateau, time t_1, signifies the time at which equilibrium is reached, as the concentrations of products and reactants is constant.

Aside from analysing concentration-time graphs, we can also use the stoichiometric ratios of reactants and products in a chemical equation to draw these graphs ourselves. For example, consider the equation for the decomposition of dinitrogen tetroxide.

$N_2O_4(g) \rightleftharpoons 2NO_2(g)$

In this reaction, we can see that for each mole of N_2O_4 (dinitrogen tetroxide) that decomposes, 2 moles of NO_2 (nitrogen dioxide) are produced. Therefore, we expect that as this reaction reaches equilibrium, the magnitude of the change in concentration of NO_2 will be twice that of N_2O_4. Figure 4 shows how we can represent this in a concentration-time graph.

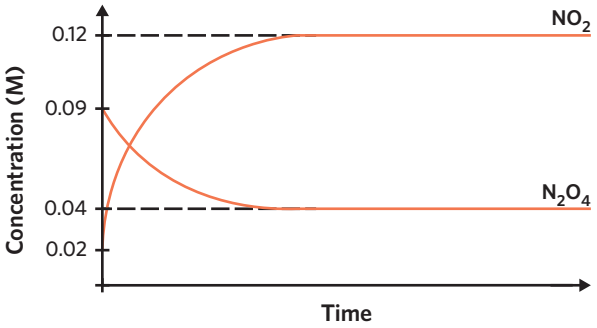


Figure 4 Concentration-time graph for the decomposition of N_2O_4

In figure 4, we can see that the initial concentrations of N_2O_4 and NO_2 were 0.09 M and 0.02 M respectively. We can also see that the concentrations of N_2O_4 and NO_2 at equilibrium are 0.04 M and 0.12 M respectively. We can calculate the changes in concentration to confirm that they align with the stoichiometric ratios.

$\Delta[N_2O_4] = c_{final} - c_{initial}$

$\Delta[N_2O_4] = 0.04\ M - 0.09\ M$

$\Delta[N_2O_4] = -0.05\ M$

$\Delta[NO_2] = c_{final} - c_{initial}$

$\Delta[NO_2] = 0.12\ M - 0.02\ M$

$\Delta[NO_2] = +0.10\ M$

We can see that the $[N_2O_4]$ has decreased by 0.05 M, whilst the $[NO_2]$ has increased by 0.10 M. Therefore, the magnitude of the change in the $[NO_2]$ is twice that of $[N_2O_4]$, which aligns with the stoichiometric ratios indicated by the reaction equation.

MISCONCEPTION

'Equilibrium can only be approached via the forward reaction.'

Equilibrium can be approached via either the forward or reverse reactions. In other words, a system containing only products to begin with can still approach equilibrium.

WORKED EXAMPLE 1

Consider the equation for the decomposition of phosphorus(V) chloride.

$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$

PCl_5 is added to a reaction vessel at a concentration of 1.3 M and allowed to decompose. At equilibrium, the concentration of PCl_5 in the reaction vessel is 1.0 M. Draw a labelled concentration-time graph for this reaction.

What information is presented in the question?

The equation for the decomposition of phosphorus(V) chloride.

Initial concentration of $PCl_5 = 1.3$ M.

Equilibrium concentration of $PCl_5 = 1.0$ M.

What is the question asking us to do?

Draw a labelled concentration-time graph for the decomposition of phosphorus(V) chloride.

What strategies do we need in order to answer the question?

1. Determine the ratios of products to reactants using stoichiometry.
2. Use the stoichiometric ratios to determine the concentration of PCl_3 and Cl_2 present at equilibrium.
3. Draw a fully labelled graph representing these changes in concentration.

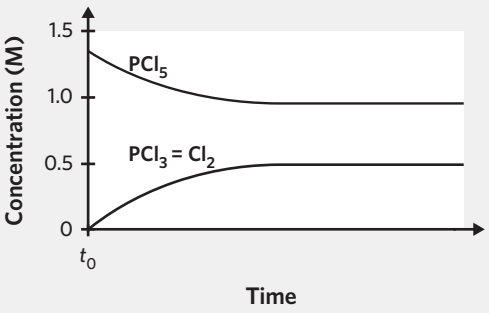
Answer

Based on the equation

$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$

For each mole of PCl_5 that decomposes, 1 mol of PCl_3 is produced and 1 mol of Cl_2 is produced. Therefore, the concentrations of both PCl_3 and Cl_2 should increase by the same amount that the concentration of PCl_5 has decreased.

Given the concentration of PCl_5 has decreased by 0.3 M, the concentrations of PCl_3 and Cl_2 should both increase by 0.3 M. Therefore, we can draw the fully labelled graph shown below.



How are rate-time graphs used to represent equilibrium reactions?

Equilibrium reactions can also be represented using rate-time graphs (figure 5).

In figure 5, we can see that the rate of the reverse reaction initially increases and the rate of the forward reaction initially decreases until the system reaches equilibrium. We know that the system has reached equilibrium as both reactions plateau at an equal rate of reaction.

In chapter 4, we learned about the effects of altering experimental conditions on the rate of a reaction. We can represent these changes in rate-time graphs, as shown in figure 6.

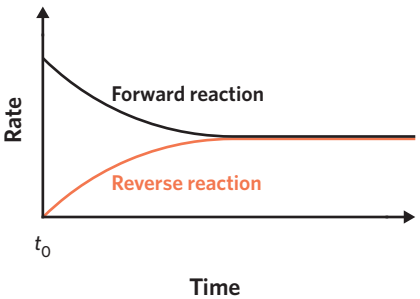


Figure 5 A generic rate-time graph

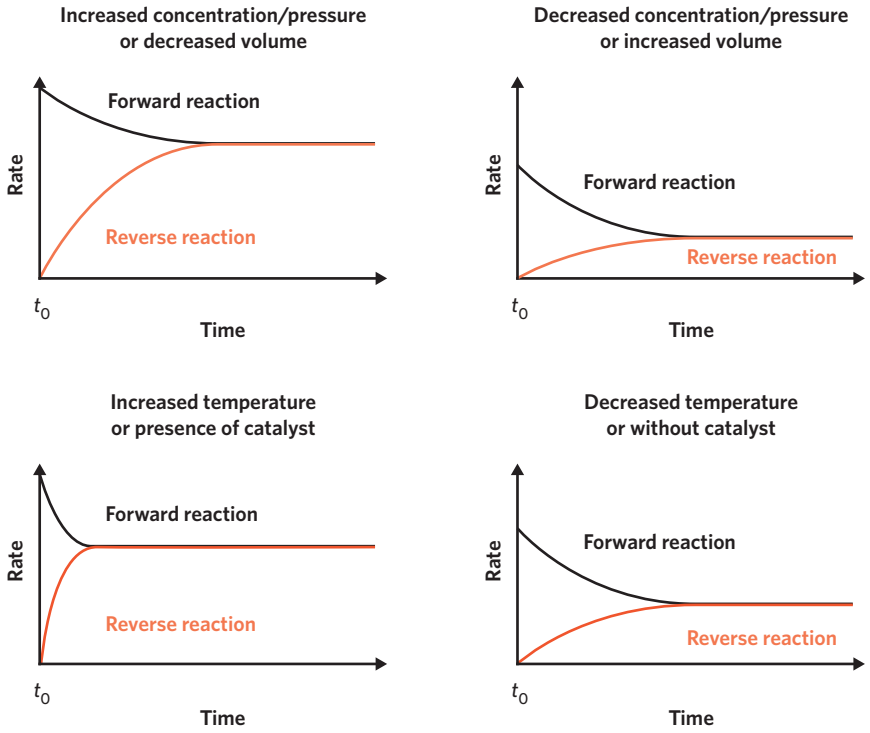
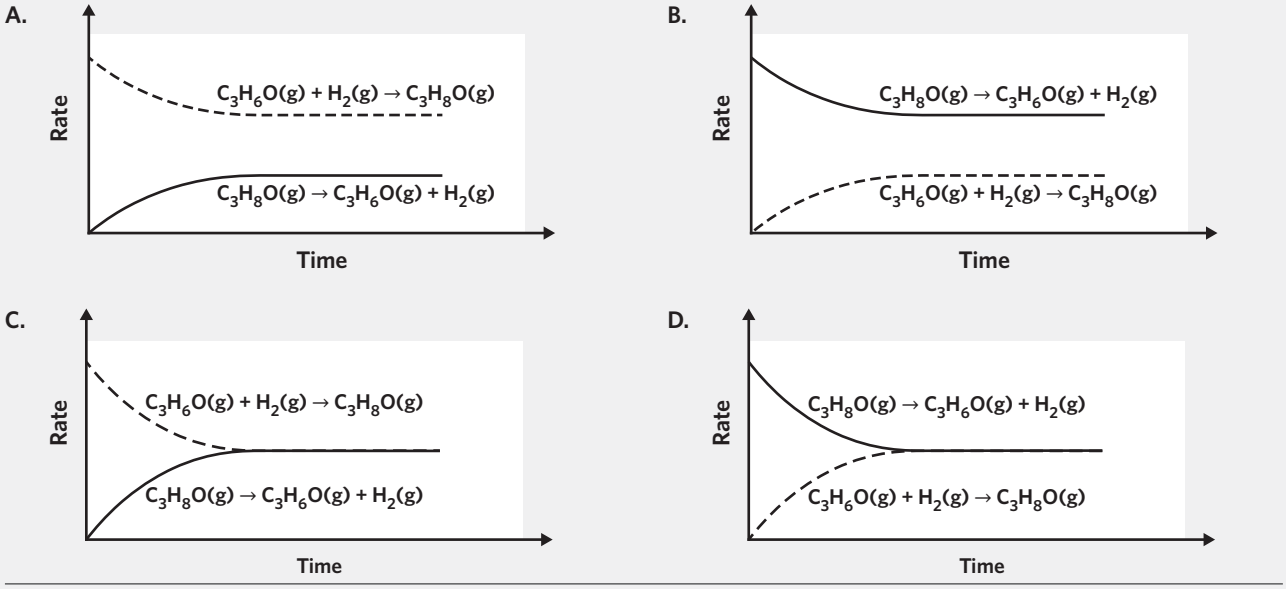


Figure 6 Rate-time graphs representing factors that affect the rate of reaction

WORKED EXAMPLE 2

When 2-propanol (C_3H_8O) reacts to form an equilibrium mixture with propanone (C_3H_6O) and hydrogen (H_2), which of the following graphs best represents how the rates of the forward and reverse reactions change over time?



What information is presented in the question?

An equilibrium mixture is formed between 2-propanol, propanone and hydrogen.

Four different rate-time graphs.

What is the question asking us to do?

Determine which of the graphs best represents how the forward and reverse reactions change over time.

What strategies do we need in order to answer the question?

1. Determine which reaction (forward or reverse) will initially decrease in rate.
2. Determine which reaction (forward or reverse) will initially increase in rate.
3. Recall the relationship between the rates of the forward and reverse reactions at equilibrium.

Continues →

Answer

We are told that 2-propanol reacts to form propanone and hydrogen, so the forward reaction is

$C_3H_8O(g) \rightarrow C_3H_6O(g) + H_2(g)$

We can first rule out options A and B as the graphs do not indicate that the rates of the forward and reverse reactions are equal at equilibrium.

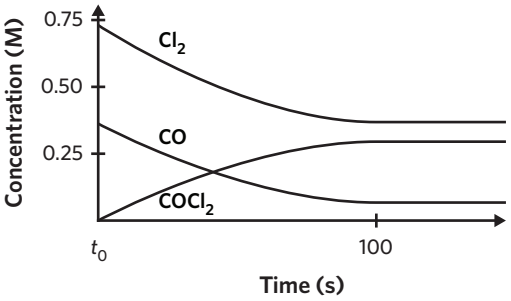
Since only 2-propanol is initially present in the equilibrium system, the forward reaction must start with a non-zero rate of reaction, whilst the rate of the reverse reaction must initially be at zero. Therefore, for the rates of the forward and reverse reactions to be equal at equilibrium, the rate of the forward reaction must decrease and the rate of the reverse reaction must increase.

The graph in option D shows the rate of the forward reaction initially decreasing and the rate of the reverse reaction initially increasing, so option D is the correct answer.

Adapted from VCAA 2007 Exam 1 Multiple choice Q7

PROGRESS QUESTIONS

Use the following concentration-time graph to answer questions 11–13.



Question 11

The initial concentration of Cl_2 is closest to

A. 0.00 M

B. 0.10 M

C. 0.40 M

D. 0.75 M

Question 12

Which of the following best describes what occurs at 100 seconds?

A. $COCl_2$ stops forming entirely.

B. The concentrations of CO and Cl_2 become equal.

C. The concentrations of $COCl_2$, CO, and Cl_2 become constant.

D. The rate of $COCl_2$ formation exceeds the rate of $COCl_2$ decomposition.

Question 13

Which of the following best represents the balanced equation for the decomposition of $COCl_2$?

A. $COCl_2 \rightleftharpoons CO + Cl_2$

B. $COCl_2 \rightleftharpoons CO + 2Cl_2$

C. $2COCl_2 \rightleftharpoons CO + Cl_2$

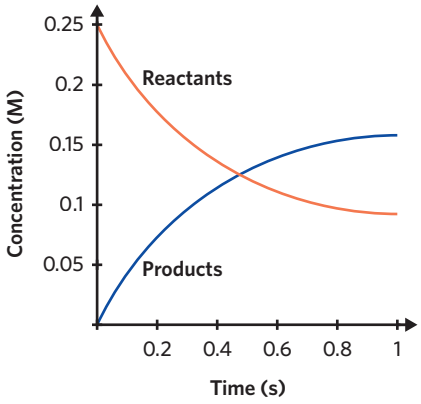
D. $COCl_2 \rightleftharpoons 2CO + 3Cl_2$

Theory summary

- An irreversible reaction can only proceed in one direction and cannot be reversed.
  - Equations for irreversible reactions are represented by a unidirectional arrow (→).
- A reversible reaction can proceed in both directions, meaning the products can reform the reactants.
  - Equations for reversible reactions are represented by a bidirectional arrow (⇌).
- The rate of a chemical reaction is a measure of the amount of product formed in a given period of time.
- The extent of a chemical reaction is a measure of the proportion of reactants that have been converted into products.
- The percentage yield of a chemical reaction can be used as a measure of the extent of a reaction, and is given by

$$\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

- The equilibrium constant (K) is a quantitative measure of the extent of a chemical reaction.
- In dynamic equilibrium:
  - The rates of the forward and reverse reactions are equal.
  - The concentrations of reactants and products are constant, but not necessarily equal.
  - Products and reactants are constantly forming and being broken down.
- Equilibrium reactions can be represented using concentration-time graphs.



5A Questions

Mild Medium Spicy

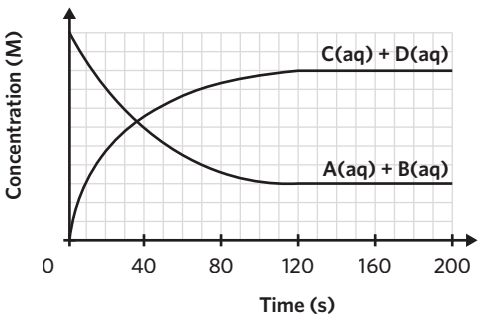
Deconstructed

Use the following information to answer questions 14–16.

A dynamic equilibrium is established when solution A is mixed with solution B at a constant temperature.

$A(aq) + B(aq) \rightleftharpoons C(aq) + D(aq)$

The graph provided shows the changes in concentrations of the reactants and products over time. Assume the volume of the reaction vessel is constant.



Question 14 (1 MARK)

At what time is equilibrium first established?

A. 10 seconds

B. 45 seconds

C. 120 seconds

D. 160 seconds

Question 15 (1 MARK)

Which of the following statements is true for this equilibrium system?

A. Only A(aq) and B(aq) were initially present in the system.

B. Only C(aq) and D(aq) were initially present in the system.

C. A(aq), B(aq), C(aq) and D(aq) were all initially present in the system.

D. None of the above are true for this equilibrium system.

Question 16 (3 MARKS)

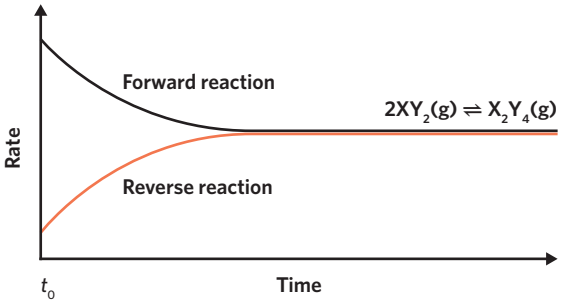
Explain how the rates of the forward and reverse reactions change in this equilibrium system over time.

Exam-style

Question 17 (1 MARK)

Consider the equation and associated rate-time graph shown.

$2XY_2(g) \rightleftharpoons X_2Y_4(g)$



For the given equilibrium reaction, the rate-time graph shown would best represent which of the following scenarios?

A. The reaction vessel initially contained only $XY_2(g)$.

B. The reaction vessel initially contained only $X_2Y_4(g)$.

C. The reaction vessel initially contained both $XY_2(g)$ and $X_2Y_4(g)$.

D. The reaction vessel initially contained neither $XY_2(g)$ nor $X_2Y_4(g)$.

Question 18 (1 MARK)

Some gaseous PCl_5 is added to an empty container, and the resulting closed system is allowed to reach equilibrium.

At equilibrium, the mass of the gas mixture, compared to the initial mass of PCl_5, is

A. halved.

B. unchanged.

C. one and a half times greater.

D. doubled.

Adapted from VCAA 2008 Exam 2 Multiple choice Q10

Question 19 (8 MARKS)

Consider the equilibrium reaction between the iron(III) ion and thiocyanate ion (SCN^-).

$Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons FeSCN^{2+}(aq) \quad \Delta H < 0$

a. Give two features of this reaction at equilibrium. 2 MARKS

b. Explain how the presence of a catalyst would affect the yield of the $FeSCN^{2+}$ ion. 3 MARKS

c. $FeSCN^{2+}(aq)$ is added to a vessel and allowed to react. Draw a rate-time graph showing the catalysed and uncatalysed equilibrium systems for this reaction. 3 MARKS

Key science skills

Question 20 (5 MARKS)

The Haber-Bosch process is used to mass-produce ammonia from nitrogen and hydrogen. In industry, the conditions at which the Haber-Bosch process is carried out are integral to the efficiency of ammonia production.

a. The following table shows the percentage yield of ammonia under varying pressures and temperatures.

Pressure (atm)	Temperature (°C)				
	100	200	300	400	500
	Yield of ammonia (%)				
10	88	51	15	4	1
50	95	75	40	15	6
100	97	82	53	25	11
200	98	89	67	40	18
400	99	95	80	55	32

i. Using the data in the table, which conditions provide the highest yield of ammonia? 1 MARK

ii. Identify one disadvantage of using lower temperatures to produce ammonia. 1 MARK

iii. Suggest how the disadvantage in part **ii** could be addressed. 1 MARK

b. In industrial settings, the actual pressure used is typically around 200 atmospheres. Suggest two disadvantages of using a higher pressure. 2 MARKS

FROM LESSONS 12B & 12C

Questions from multiple lessons

Question 21 (5 MARKS)

Nitrogen oxides are commonly found in the atmosphere in areas where there is serious atmospheric pollution. Nitrogen monoxide, NO, is generated from the reaction between nitrogen and oxygen.

$N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$

a. Is the formation of nitrogen monoxide from nitrogen and oxygen a redox reaction? Justify your answer using oxidation states. 2 MARKS

b. A sealed container is filled with 1.00 mol of NO(g) and equilibrium is established. The temperature is maintained at 1500 °C. Explain why the rate of the reaction

$N_2(g) + O_2(g) \rightarrow 2NO(g)$

will never be greater than the rate of the reaction

$2NO(g) \rightarrow N_2(g) + O_2(g)$

i. while the system is reaching equilibrium. 2 MARKS

ii. once equilibrium is established. 1 MARK

Adapted from VCAA 2011 Exam 2 Short answer Q5a

FROM LESSON 3A

Back to contents

5B Calculating equilibrium constants

STUDY DESIGN DOT POINTS

- the dynamic nature of homogenous equilibria involving aqueous solutions or gases, and their representation by balanced chemical or thermochemical equations (including states) and by concentration-time graphs
- calculations involving equilibrium expressions (including units) for a closed homogeneous equilibrium system and the dependence of the equilibrium constant (K) value on the system temperature and the equation used to represent the reaction
- the reaction quotient (Q) as a quantitative measure of the extent of a chemical reaction: that is, the relative amounts of products and reactants present during a reaction at a given point in time

5A 5B 5C 5D

3.2.7.3 Equilibrium law and equilibrium constant

3.2.8.4 Reaction quotient (Q)

ESSENTIAL PRIOR KNOWLEDGE

1D Endothermic and exothermic reactions

5A Extent of a reaction

See questions 38–39.



Why does temperature change the colour of certain chemical reactions?

It is possible to observe differences in the extent of chemical reactions when changes to the closed equilibrium system are applied. In this lesson, we will learn about the expressions for the **equilibrium constant** and **reaction quotient**, as well as the information they provide about an equilibrium system. We will also explore the effect of temperature on the equilibrium constant.

KEY TERMS AND DEFINITIONS

Endothermic reaction chemical reaction that absorbs energy (in the form of heat) from the surrounding environment

Equilibrium constant (K) the value of the concentration fraction for a system at equilibrium

Equilibrium expression $K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$

Equilibrium law the value of K is the ratio of the concentrations of the products to the concentrations of the reactants i.e. $K = \frac{[\text{products}]}{[\text{reactants}]}$

Exothermic reaction chemical reaction accompanied by the release of energy (in the form of heat)

Reaction quotient (Q) the value of the concentration fraction for a system that is not at equilibrium

Equilibrium law and equilibrium constant 3.2.7.3

Calculations involving **equilibrium expressions** are an important tool in understanding the behaviour of equilibrium systems.

How can we calculate concentrations in a closed, homogeneous equilibrium system?

As we learned in lesson 5A, dynamic equilibrium is the point at which the forward and reverse reactions of a chemical system are occurring at equal rates, resulting in no net change in the concentrations of the reactants or products. When a closed, homogeneous system establishes equilibrium, the equilibrium constant, K, can be calculated using the concentrations of the reactants and products at equilibrium.

USEFUL TIP

Recall that in VCE chemistry, [ ] is used to denote the concentration of the chemical in mol L^{-1} or M.

Equilibrium law states that the value of K is the ratio of the concentrations of the products to the concentrations of the reactants. This law is represented formulaically as $K = \frac{[\text{products}]}{[\text{reactants}]}$. Using this, we can carry out a number of calculations involving equilibrium systems.

For the general equation

$aA + bB \rightleftharpoons cC + dD$

The equilibrium expression is:

$$K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

When we know the relative concentrations of products and reactants in a system at equilibrium, we can calculate the value of K. For example, consider the reaction between hydrogen and iodine gas to form hydrogen iodide shown.

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

In one case, the concentrations of H_2, I_2 and HI at equilibrium are 0.500 M, 0.400 M and 1.10 M respectively. Therefore, we can calculate the equilibrium constant for this particular case as follows.

$$K = \frac{[HI]^2}{[H_2][I_2]}$$

$$K = \frac{(1.10\ \text{M})^2}{0.500\ \text{M} \times 0.400\ \text{M}}$$

$K = 6.05$ (no units)

USEFUL TIP

Regardless of what an equation looks like, the equilibrium constant is always equal to the right-hand side of the equation divided by the left-hand side of the equation

i.e. $K = \frac{[\text{right}]}{[\text{left}]}$

WORKED EXAMPLE 1

Consider the following equilibrium expression.

$$K = \frac{[L][M]^4}{[J]^6[K]}$$

The equation of the forward reaction for this equilibrium expression is

A. $6J + K \rightleftharpoons L + 4M$

B. $L + M_4 \rightleftharpoons J_6 + K$

C. $J_6 + K \rightleftharpoons L + M_4$

D. $L + 4M \rightleftharpoons 6J + K$

What information is presented in the question?

The equilibrium expression for a reaction.

What is the question asking us to do?

Determine the equation of the forward reaction for the given equilibrium expression.

Continues →

What strategies do we need in order to answer the question?

1. Recall the general formula for an equilibrium expression.
2. Use this formula to determine the equation that the given equilibrium expression represents.

Answer

For the general equation

$aA + bB \rightleftharpoons cC + dD$

The equilibrium expression is:

$$K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

Therefore, for $K = \frac{[L][M]^4}{[J]^6[K]}$

The left-hand side of the equation for the forward reaction will be the denominator of the expression:

$6J + K \rightleftharpoons \ldots$

And the right-hand side of the equation for the forward reaction will be the numerator of the expression:

$\ldots \rightleftharpoons L + 4M$

Giving us the overall equation:

$6J + K \rightleftharpoons L + 4M$

Hence, the answer is **option A**.

Adapted from VCAA 2011 Exam 2 Multiple choice Q1

MISCONCEPTION

'Any units of concentration can be used in equilibrium expression calculations.'

Since the value of the equilibrium constant depends on the mole ratios of reactants and products in a reaction equation, molar concentration (M or mol L^{-1}) must always be used when carrying out calculations involving equilibrium constants.

When carrying out calculations involving equilibrium constants, it's important to be careful with the coefficients of each species in a reaction equation for two reasons. Firstly, the coefficients are used as the indices to which the concentrations of each species are raised, and secondly, they dictate the unit of the equilibrium constant for a given reaction.

For example, consider the equation for the production of ammonia from nitrogen and hydrogen.

$1N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

Here, we can see that 1 mol of nitrogen gas and 3 mol of hydrogen gas react to form 2 mol of ammonia gas. Therefore, the units for the equilibrium expression for this reaction can be calculated as follows:

$$\frac{M^2}{M^1 \times M^3} = \frac{M^2}{M^4}$$

$$\frac{M^2}{M^4} = M^{2-4}$$

$M^{2-4} = M^{-2}$ (or $mol^{-2}\ L^2$)

MISCONCEPTION

'Every equilibrium constant has units.'

For some equations, all concentration terms will cancel, resulting in no units.

STRATEGY

A simpler way to determine the units of an equilibrium constant is to subtract the total number of units on the left from the total number of units on the right.

For the equation $1N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

$Right - Left = 2 - (1 + 3)$

$Right - Left = -2$

Therefore, the unit of K is M^{-2}

WORKED EXAMPLE 2

Consider the equation shown.

$CO(g) + Cl_2(g) \rightleftharpoons COCl_2(g)$

A sealed 2.00 L reaction vessel contains 3.00 mol of CO(g), 2.00 mol of $Cl_2(g)$ and 2.50 mol of $COCl_2(g)$ when the system establishes equilibrium. Calculate the equilibrium constant for this reaction.

What information is presented in the question?

A chemical equation.

The volume of the reaction vessel is 2.0 L.

The amounts in mol of species present at equilibrium.

What is the question asking us to do?

Calculate the value of the equilibrium constant for this reaction.

What strategies do we need in order to answer the question?

1. Calculate the concentration of each species at equilibrium using the formula from the VCE Data Book $c = \frac{n}{V}$.
2. Determine the equilibrium expression for this reaction.
3. Substitute the concentrations of each species into the equilibrium expression.
4. Determine the appropriate value, significant figures, and units for the equilibrium constant.

Answer

To determine the equilibrium constant, we need to calculate the concentrations of the reactants and the products.

$$c(\text{CO}) = \frac{3.00 \text{ mol}}{2.00 \text{ L}}$$

$$c(\text{CO}) = 1.50 \text{ M}$$

$$c(\text{Cl}_2) = \frac{2.00 \text{ mol}}{2.00 \text{ L}}$$

$$c(\text{Cl}_2) = 1.00 \text{ M}$$

$$c(\text{COCl}_2) = \frac{2.50 \text{ mol}}{2.00 \text{ L}}$$

$$c(\text{COCl}_2) = 1.25 \text{ M}$$

Using the equation given, the equilibrium expression is

$$K = \frac{[\text{COCl}_2]}{[\text{CO}][\text{Cl}_2]}$$

Therefore, we can substitute the concentrations of the product and reactants in to calculate the value of the equilibrium constant.

$$K = \frac{1.25 \text{ M}}{1.50 \text{ M} \times 1.00 \text{ M}}$$

$$K = 0.833$$

We can now calculate the units of the equilibrium constant as follows:

$$\frac{\text{M}}{\text{M} \times \text{M}} = \frac{\text{M}}{\text{M}^2}$$

$$\frac{\text{M}}{\text{M} \times \text{M}} = \text{M}^{-1}$$

Therefore, the final answer is $K = 0.833 \text{ M}^{-1}$.

The equilibrium expression for a given reaction always refers to the equation exactly as it's written. Therefore, if the mole coefficients on each species are doubled, then the equation is written as

$2aA + 2bB \rightleftharpoons 2cC + 2dD$

And so the equilibrium expression must be written as

$$K = \frac{[\text{C}]^{2c}[\text{D}]^{2d}}{[\text{A}]^{2a}[\text{B}]^{2b}}$$

Which is equivalent to

$$K = \left(\frac{[\text{C}]^{c}[\text{D}]^{d}}{[\text{A}]^{a}[\text{B}]^{b}}\right)^2$$

Therefore, doubling all coefficients in the reaction equation is equivalent to squaring the equilibrium expression. In general, multiplying all reaction coefficients by x causes K (and its unit) to be raised to the power of x.

Similarly, if the reaction is written in reverse, the value of K will be the reciprocal of the forward reaction.

$$K_{reverse} = \frac{1}{K_{forward}}$$

WORKED EXAMPLE 3

Consider the equations shown below.

(1) $CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g)$ $\quad K_1 = 4.3\ M^{-2}$ at 250 °C

(2) $2CH_3OH(g) \rightleftharpoons 2CO(g) + 4H_2(g)$ $\quad K_2 = ?$

Calculate the value of K_2 at 250 °C.

What information is presented in the question?

The equation for the synthesis of methanol and the equilibrium constant for the reaction at 250 °C.

A second equation for the formation of carbon monoxide and hydrogen from methanol.

What is the question asking us to do?

Calculate the magnitude of K_2.

What strategies do we need in order to answer the question?

1. Determine the relationship between equations (1) and (2).
2. Recall the formulas for calculating K when coefficients are changed and when a reaction is reversed.
3. Use the formulas to calculate K_2.

Answer

Looking at equation (2), we can see that it is the result of doubling the coefficients in equation (1) and reversing it. If the mole coefficients on each species are doubled, then the equilibrium expression is written as:

$$K = \left(\frac{[CO][H_2]^2}{[CH_3OH]}\right)^2$$

And if the reaction is written in reverse and doubled, the value of K will be the reciprocal of the forward reaction squared.

$$K_{reverse} = \left(\frac{1}{K_{forward}}\right)^2$$

Therefore at 250 °C,

$$K_2 = \left(\frac{1}{K_1}\right)^2$$

$$K_2 = \frac{1^2}{4.3^2}$$

$$K_2 = 0.054$$

The unit of K_2 can be determined:

Directly from equation (2) as 6 sets of units on the right minus 2 sets of units on the left = M^4.

Or, by taking $\frac{1}{(M^{-2})^2}$, because $K_2 = \frac{1}{K_1{}^2}$ and M^{-2} is the unit of K_1.

Therefore, the final answer is $K_2 = 0.054\ M^4$.

MISCONCEPTION

'The value of *K* will not change if all the concentrations are halved.'

The value of *K* does not depend on the coefficients from the balanced equation, but the values of the concentrations of reactants and products at equilibrium are affected by the coefficients from the balanced equation.

In some cases, the equilibrium constant for a particular reaction may be known, as well as the concentrations of some species both initially and when the system reaches equilibrium. In cases like these, we can use stoichiometric ratios to predict unknown concentrations either initially or when the system reaches equilibrium. To do this, we can use *n*ICE tables, where ***n*** represents the **n**umber of equivalent moles taken from the stoichiometric ratios in the balanced chemical equation, **I** stands for **i**nitial concentration, **C** stands for change in **c**oncentration, and **E** stands for concentration at **e**quilibrium, such as that shown in table 1.

Table 1 Incomplete *n*ICE table for the reaction $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

Concentration (M)	$N_2(g)$	+	$3H_2(g)$	⇌	$2NH_3(g)$
n ratio	1		3		2
Initial	1.00		3.00		0.00
Change	–		–		–
Equilibrium	0.60		–		–

In table 1, we can see that the **I**nitial concentrations of $N_2(g)$ and $H_2(g)$ were 1.00 M and 3.00 M respectively, whilst there was initially no $NH_3(g)$ in the reaction vessel. Since the concentration of $N_2(g)$ is 0.60 M at **E**quilibrium, we can say that the change in the concentration of $N_2(g)$ is −0.40 M. Using the ***n*** ratios, we expect that the **C**hange in the concentration of $N_2(g)$ should be a third of that of $H_2(g)$, and half of that of $NH_3(g)$. Hence, the change in the concentration of $H_2(g)$ will be −1.20 M and the change in the concentration of $NH_3(g)$ will be +0.80 M, giving us the completed *n*ICE table (table 2).

Table 2 Completed *n*ICE table for the reaction $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

Concentration (M)	$N_2(g)$	+	$3H_2(g)$	$\rightleftharpoons$	$2NH_3(g)$
n ratio	1		3		2
Initial	1.00		3.00		0.00
Change	−0.40		−1.20		+0.80
Equilibrium	0.60		1.80		0.80

In table 2, we can see that the changes in the concentrations of both $N_2(g)$ and $H_2(g)$ are negative. Since both reactants are used up in the formation of $NH_3(g)$, if the concentration of one reactant decreases, then the concentration of the other reactant must also decrease. Since a decrease in the concentration of a reactant indicates that it has been used up to form products, we know that the concentration of the products must increase, resulting in the positive change in concentration of NH_3.

USEFUL TIP

When using *n*ICE tables, ensure you use either molar amounts or concentrations for all values – not a mix of both. Sometimes, you may need to convert values before constructing the table, and in other cases, you may need to convert values at the end to obtain the final answer.

USEFUL TIP

When water is present as a liquid in an equilibrium system, it is omitted from the equilibrium expression because its concentration does not change significantly as the system reaches equilibrium.

STRATEGY

To determine whether the concentrations of each species are increasing or decreasing, we can use the equation for the reaction. If the concentration of a chemical on the left-hand side of the equation is increasing, then the concentrations of all chemicals on the left-hand side must be increasing and the concentrations of all chemicals on the right-hand side must be decreasing, and vice versa.

WORKED EXAMPLE 4

Hydrogen and iodine react together to form hydrogen iodide according to the following equilibrium reaction.

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

0.40 mol of $H_2(g)$, 0.70 mol of $I_2(g)$ and 0.10 mol of HI(g) were initially present in a 5.0 L reaction vessel, and the system was allowed to reach equilibrium. At equilibrium, the concentration of HI(g) was 0.14 M. Calculate the amount of H_2, in mol, present in the reaction vessel at equilibrium.

What information is presented in the question?

The equation for the reaction between hydrogen and iodine.

The volume of the reaction vessel is 5.0 L.

Initial amounts of each species:

$n(H_2) = 0.40$ mol

$n(I_2) = 0.70$ mol

$n(HI) = 0.10$ mol

The concentration of HI at equilibrium:

$c(HI) = 0.14$ M

What is the question asking us to do?

Calculate the amount of H_2, in mol, present in the reaction vessel at equilibrium.

What strategies do we need in order to answer the question?

1. Convert all values to either molar amounts or concentration.
2. Construct a *n*ICE table with all known information filled in.
3. Use stoichiometric ratios from the reaction equation to complete the *n*ICE table.

Continues →

Answer

Since our final answer should be in mol, and since all initial values are given in mol, it will be easiest to convert the concentration of HI at equilibrium to a molar amount.

$n(\text{HI}) = c \times V$

$n(\text{HI}) = 0.14\ \text{M} \times 5.0\ \text{L}$

$n(\text{HI}) = 0.70\ \text{mol}$

Amount (mol)	$H_2(g)$ +	$I_2(g)$ ⇌	$2HI(g)$
n ratio	1	1	2
Initial	0.40	0.70	0.10
Change	−	−	−
Equilibrium	−	−	0.70

From the *n*ICE table, we can see that the amount of HI present has increased by 0.60 mol. Using the stoichiometric ratios, the magnitude of the changes in the amounts of H_2 and I_2 should be half that of the change in HI. Therefore, the magnitude of the change in the amounts of both H_2 and I_2 is 0.30 mol. Since the amount of the product has increased, we know that the amounts of the reactants must decrease as they are used up to form the product, so the change in the amounts of both H_2 and I_2 is −0.30 mol. We can add this information to the *n*ICE table as shown below.

Amount (mol)	$H_2(g)$ +	$I_2(g)$ ⇌	$2HI(g)$
n ratio	1	1	2
Initial	0.40	0.70	0.10
Change	−0.30	−0.30	+0.60
Equilibrium	0.10	0.40	0.70

Hence, given that 0.40 mol of H_2 was initially present, and that this amount decreased by 0.30 mol, 0.10 mol of H_2 was present in the reaction vessel at equilibrium.

How can the equilibrium constant change with temperature?

In chapter 4, we looked at various factors that can affect the rate of a reaction. Of these factors, only temperature can affect the value of *K*. This is because temperature changes are the only changes that actually alter the energy available to the system. When the energy available to the system is altered, the reactants and products adjust to share that energy, which can affect the ratio of products to reactants in the system. As we know, the equilibrium expression describes the ratio of products to reactants, and thus, the value of *K* changes when this ratio changes.

For systems in which the forward reaction is **endothermic** ($\Delta H > 0$), an increase in temperature will lead to an increase in the extent of the reaction, and hence an increase in the value of *K*.[1] On the contrary, for systems in which the forward reaction is **exothermic** ($\Delta H < 0$), an increase in temperature will lead to a decrease in the extent of the reaction, and hence a decrease in the value of *K*. In lesson 5C, we will discuss why this is the case in further detail.

KEEN TO INVESTIGATE?

[1] **How do temperature changes affect the extent of a reaction?**
Search YouTube: The Effect of Temperature on Equilibrium – N_2O_4 to $2NO_2$

WORKED EXAMPLE 5

Consider the equation for the formation of hydrogen iodide from hydrogen and iodine.

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \quad \Delta H = -10.4$ kJ

For this reaction, $K = 160$ at 500 K. Which of the following is closest to the value of K at 700 K?

A. 54

B. 160

C. 500

D. 700

What information is presented in the question?

The thermochemical equation for the formation of hydrogen iodide.

The value of K at 500 K.

What is the question asking us to do?

Determine which of the options would be closest to the value of K at 700 K.

What strategies do we need in order to answer the question?

1. Determine whether the reaction is endothermic or exothermic.
2. Recall the effect of temperature increases on endothermic/exothermic reactions.

Answer

From the thermochemical equation, we can see that the enthalpy change is negative, meaning the forward reaction is exothermic. Therefore, given $K = 160$ at 500 K, if the temperature is increased to 700 K, the value of K should decrease. Hence, the correct option will be the option that is less than 160, which is **option A**.

PROGRESS QUESTIONS

Question 1

Which of the following statements is true about the equilibrium constant, K?

A. K depends on the initial concentrations of reactants and products.

B. K is always greater than 1 for an exothermic reaction.

C. K is always expressed in units of M or mol L^{-1}.

D. K can only change with temperature.

Question 2

Assume the concentration of all of the gases in the below equilibrium reactions is exactly 1.0 M.

Reaction 1 $CH_4(g) + 2H_2O(g) \rightleftharpoons CO_2(g) + 4H_2(g)$

Reaction 2 $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

Reaction 3 $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

Reaction 4 $2NO_2(g) \rightleftharpoons N_2O_4(g)$

For which reaction is $K = 1.0\ M^{-2}$?

A. Reaction 1

B. Reaction 2

C. Reaction 3

D. Reaction 4

VCAA 2019 exam Multiple choice Q28

Continues →

Question 3

Ammonia can be synthesised by reacting nitrogen, N_2, gas with hydrogen, H_2, gas according to the following equation.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92\ kJ$

The expression for the equilibrium constant for this reaction is

A. $\frac{[NH_3]}{3[H_2][N_2]}$ **B.** $\frac{2[NH_3]}{3[H_2][N_2]}$ **C.** $\frac{[NH_3]^2}{[H_2]^3[N_2]^3}$ **D.** $\frac{[NH_3]^2}{[H_2]^3[N_2]}$

VCAA (NHT) 2017 exam Multiple choice Q10

Question 4

Consider the following reaction at 25 °C.

$2A + B \rightleftharpoons C + D \quad K = 2.5 \times 10^{-3}\ M^{-1}$

If the concentration of A is doubled, what will happen to the value of K?

A. K will increase.

B. K will decrease.

C. K will remain the same.

D. The effect of the concentration of A on K cannot be determined without knowing the concentrations of B, C, and D.

Question 5

An exothermic reaction subjected to an increase in temperature will have

A. an increased rate of reaction and an increase in K.

B. an increased rate of reaction and a decrease in K.

C. a decreased rate of reaction and an increase in K.

D. a decreased rate of reaction and a decrease in K.

Reaction quotient (Q) 3.2.8.4

The reaction quotient (Q) serves as a quantitative measure of the extent of a reaction.

How can we use Q to calculate concentrations in a system that is not at equilibrium?

When a system is not at equilibrium, the reaction quotient, Q, is the expression for the ratios of the concentrations of products and reactants in the system. For example, for a system containing only reactants to begin with, we can calculate the value of Q as follows.

$$Q = \frac{0\ M}{1.0\ M \times 3.0\ M}$$

$$Q = 0\ M^{-1}$$

The value of Q can provide valuable information about what is occurring inside the reaction vessel at a given time. Recalling that the value of K is an indication of the ratios of products to reactants, if our value of Q is lower than K, then the reaction system will only reach equilibrium if the numerator (concentration of products) is increased. That is, more reactants must be converted into products. As such, when $Q < K$, we say that the forward reaction is favoured, or that the reaction is shifting to the right. If $Q > K$, the reverse reaction is favoured – or the reaction is shifting to the left – as more products are converted into reactants for the system to reach equilibrium. This idea is summarised in figure 1.

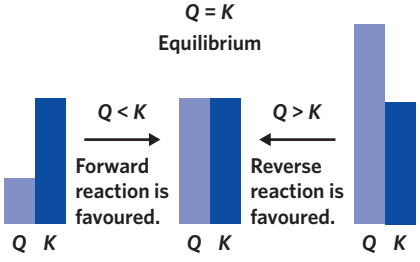


Figure 1 Summary of the relationship between Q and K

WORKED EXAMPLE 6

The values of K and Q for a system are given.

$K = 3.0 \times 10^4\ \text{M}^3 \quad Q = 22\ \text{M}^3$

Based on these values, is the system at equilibrium? If not, is the forward or reverse reaction currently favoured? Explain your answer.

What information is presented in the question?

The values of K and Q for a system.

What is the question asking us to do?

Determine whether the system is at equilibrium and explain whether the forward or reverse reaction is favoured.

What strategies do we need in order to answer the question?

1. Determine whether K and Q are equal, or which of K and Q is larger.
2. Recall the relationship between K, Q, and the shift of an equilibrium system.

Answer

Q is not equal to K, so the system is not at equilibrium. Q is less than K, so more products are being formed as the reaction approaches equilibrium. Therefore, the forward reaction is being favoured.

As we learned in lesson 5A, the value of K can be used to indicate the extent of a reaction. Similarly, Q can be used as a quantitative measure of the extent of a reaction. Since both K and Q are simply indicators of the ratio of products to reactants in a system, the extent to which a reaction has proceeded can be indicated by the difference between Q and K. A reaction that has proceeded further from equilibrium will have a greater difference between Q and K, and a reaction that has proceeded closer to equilibrium will have a lesser difference between Q and K.

MISCONCEPTION

'Q will never be equal to K.'

The value of Q is equal to K when a system is at equilibrium.

PROGRESS QUESTIONS

Question 6

What information can be determined from the value of Q?

A. The extent to which the reaction has proceeded at a given point in time

B. Whether the reaction is exothermic or endothermic

C. The activation energy of the reaction

D. The rate of the reaction

Question 7

If $Q < K$, the reaction

A. will proceed predominantly in the forward direction.

B. will proceed predominantly in the reverse direction.

C. is at equilibrium.

D. has stopped.

Question 8

What is the relationship between Q and K at equilibrium?

A. $Q > K$

B. $Q < K$

C. $Q = K$

D. There is no relationship between Q and K at equilibrium.

Theory summary

- For the reaction $aA + bB \rightleftharpoons cC + dD$, the expression for the equilibrium constant K is given by:
  $K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$
- The units of K for the reaction $aA + bB \rightleftharpoons cC + dD$ are calculated using the molar coefficients:
  $\text{Units} = \frac{M^cM^d}{M^aM^b}$
- The concentrations of reactants and products in equilibrium reactions can be modelled using *n*ICE tables to solve calculations involving unknown concentrations.
- The value of K can only be affected by a change in temperature.

Type of reaction	Change in temperature	Equilibrium constant (K)
Exothermic	Increase	Decreases
	Decrease	Increases
Endothermic	Increase	Increases
	Decrease	Decreases

- The reaction quotient (Q) is a quantitative measure of the extent of a reaction that is yet to establish equilibrium.
- For the reaction $aA + bB \rightleftharpoons cC + dD$ in a system that has not reached equilibrium, the reaction quotient Q is given by:
  $Q = \frac{[C]^c[D]^d}{[A]^a[B]^b}$
- If a reaction with equilibrium constant K_1 has all its coefficients multiplied by some number x, it will have the new equilibrium constant $K_2 = K_1{}^x$.
  - Similarly, if a reaction with the equilibrium constant $K_{forward}$ is reversed, then $K_{reverse} = \frac{1}{K_{forward}}$

5B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 9–11.

The oxidation of sulfur dioxide, SO_2, to sulfur trioxide, SO_3, can be represented by the following equation.

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \quad K = 1.75\ M^{-1}$ at 1000 °C

An equilibrium mixture has a concentration of 0.12 M SO_2 and 0.16 M oxygen gas, O_2. The temperature of the container is 1000 °C.

Question 9 (1 MARK)

What is the expression for the equilibrium constant for this reaction?

A. $\frac{[SO_3]}{[SO_2] + [O_2]}$

B. $\frac{2[SO_3]}{2[SO_2][O_2]}$

C. $\frac{[SO_3]^2}{[SO_2]^2[O_2]}$

D. $\frac{[SO_2]^2[O_2]}{[SO_3]^2}$

Question 10 (1 MARK)

Which of the following expressions can be used to calculate $[SO_3]$ at equilibrium?

A. $[SO_3] = K \times [SO_2][O_2]$

B. $[SO_3] = \dfrac{K}{[SO_2][O_2]}$

C. $[SO_3] = \sqrt{K \times [SO_2]^2[O_2]}$

D. $[SO_3] = \sqrt{\dfrac{K}{[SO_2]^2[O_2]}}$

Question 11 (1 MARK)

The equilibrium concentration of SO_3 at 1000 °C is

A. 1.5×10^{-4} M

B. 4.0×10^{-3} M

C. 1.2×10^{-2} M

D. 6.3×10^{-2} M

Adapted from VCAA 2019 exam Multiple choice Q20

Exam-style

Question 12 (1 MARK)

The equilibrium constant (K) for the reaction A + B ⇌ C is 0.050 M^{-4} at 25°C. What is the equilibrium constant (K) for the reaction 2A + 2B ⇌ 2C?

A. 0.0025

B. 0.025

C. 0.050

D. 0.10

Question 13 (1 MARK)

$Br_2(g) + I_2(g) \rightleftharpoons 2IBr(g) \quad K = 1.2 \times 10^2$ at 150 °C

Given the information above, what is the value of K for the following reaction at 150 °C?

$4IBr(g) \rightleftharpoons 2Br_2(g) + 2I_2(g)$

A. 1.6×10^{-2}

B. 4.1×10^{-3}

C. 6.9×10^{-5}

D. 8.03×10^{-5}

Adapted from VCAA 2018 exam Multiple choice Q27

Question 14 (1 MARK)

The following reaction, in which dinitrogen tetroxide, N_2O_4, is converted to nitrogen dioxide, NO_2, forms an equilibrium.

$N_2O_4(g) \rightleftharpoons 2NO_2(g)$

At a given temperature, the equilibrium constant for this reaction is 3.15 M and the molar concentration of N_2O_4 at equilibrium is 0.350 M. At this temperature, the molar concentration of NO_2 at equilibrium is

A. 0.550 M

B. 1.05 M

C. 1.10 M

D. 3.00 M

VCAA (NHT) 2018 exam Multiple choice Q19

Question 15 (13 MARKS)

Carbon monoxide reacts with ammonia to form an equilibrium according to the following equation.

$2CO(g) + NH_3(g) \rightleftharpoons HCN(g) + CO_2(g) + H_2(g)$

At a temperature T_1 the equilibrium constant for the reaction is $K = 0.175$. A 7000 L reaction vessel is maintained consistently at this temperature.

a. Write an expression for the equilibrium constant, K. 1 MARK

b. Initially, the concentrations of reactants in the 7000 L vessel are as follows:

$[CO] = 0.163$ M

$[NH_3] = 40.00$ M

$[HCN] = 13.40$ M

$[CO_2] = 15.30$ M

$[H_2] = 19.20$ M

i. At this temperature T_1, in which direction will the reaction proceed in order to establish equilibrium? Justify your answer using a calculation. 2 MARKS

ii. At equilibrium, $[H_2] = 13.60$ M. Calculate the amount, in grams, of NH_3 present at equilibrium. 3 MARKS

iii. A chemist lowers the temperature of the reaction vessel to a new temperature T_2. At this new temperature, the equilibrium concentration of HCN is 0.00100 M. Calculate the value (including units) of the equilibrium constant for this reaction at the new temperature T_2. 3 MARKS

iv. Is the production of HCN via this reaction endothermic or exothermic? Explain. 2 MARKS

c. A second method of producing hydrogen cyanide also uses ammonia but involves methane and oxygen instead of carbon monoxide. The equilibrium reaction for this process is given below.

$2CH_4(g) + 2NH_3(g) + 3O_2(g) \rightleftharpoons 2HCN(g) + 6H_2O(g)$

At the same temperature T_1, it is observed that this second reaction results in a much higher rate of production of HCN compared with the process described by the first reaction. From this information alone, is it possible to determine anything about the relative magnitude of this second reaction's equilibrium constant compared with that of the first reaction? Explain. 2 MARKS

Key science skills

Question 16 (8 MARKS)

Consider the reaction shown in the following equation.

$2NO(g) + Br_2(g) \rightleftharpoons 2NOBr(g) \quad \Delta H = -16.1$ kJ, $K = 1.3 \times 10^{-2}$ M^{-1} at 1000 K

A chemist places 10.0 mol of NOBr, 10.0 mol of NO and 5.0 mol of Br_2 in a 1.0 L container at 1000 K.

a. Write an expression for the equilibrium constant for this reaction. 1 MARK

b. Predict in which direction the reaction will proceed. Justify your answer. 3 MARKS

c. The following pictogram appears on the safety data sheet for nitrogen monoxide.



i. Identify the hazard represented by this pictogram. 1 MARK

ii. Identify one precautionary measure for this hazard. 1 MARK

d. The chemist performing the investigation fails to ensure that her reaction vessel is airtight, and reports feeling a 'shortness of breath'. A fellow chemist therefore asserts that nitrogen monoxide **must** cause respiratory problems. Evaluate the chemist's assertion. 2 MARKS

Adapted from VCAA 2015 exam Short answer Q7a, b

FROM LESSONS 12A & 12B

Questions from multiple lessons

Question 17 (1 MARK)

The magnitude of the equilibrium constant, K, at 25 °C for the following reaction is 640.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92.3$ kJ

For the reaction $\frac{1}{3}N_2(g) + H_2(g) \rightleftharpoons \frac{2}{3}NH_3(g)$, the magnitude of K at 25 °C is

A. 9 and $\Delta H = -30.8$ kJ

B. 213 and $\Delta H = -30.8$ kJ

C. 640 and $\Delta H = -30.8$ kJ

D. 640 and $\Delta H = -92.3$ kJ

Adapted from VCAA 2020 exam Multiple choice Q14

FROM LESSON 1D

Use the following information to answer questions 18–19.

Hydrogen and fluorine react according to the following equation.

$\frac{1}{2}H_2(g) + \frac{1}{2}F_2(g) \rightleftharpoons HF(g) \quad \Delta H = -271$ kJ

In an experiment, 0.250 mol of hydrogen and 0.340 mol of fluorine were placed in a reaction vessel that had a volume of V litres. Once equilibrium was established, there was 0.220 mol of HF present in the reaction vessel.

Question 18 (1 MARK)

Which one of the following expressions can be used to calculate the value of the equilibrium constant for this reaction?

A. $\dfrac{[HF]}{\frac{1}{2}[H_2] + \frac{1}{2}[F_2]}$

B. $\dfrac{[HF]}{[H_2][F_2]}$

C. $\dfrac{n(HF)}{n(H_2) \times n(F_2)}$

D. $\dfrac{n(HF)}{n(H_2)^{\frac{1}{2}} \times n(F_2)^{\frac{1}{2}}}$

VCAA 2011 Exam 2 Multiple choice Q3

Question 19 (1 MARK)

The reaction vessel is surrounded by a heat exchanger that keeps the reaction mixture at a constant temperature. The amount of heat energy absorbed by the heat exchanger in order to keep a constant temperature in the reaction vessel is

A. 24.4 kJ

B. 59.6 kJ

C. 67.8 kJ

D. 92.1 kJ

VCAA 2011 Exam 2 Multiple choice Q4

FROM LESSON 2A

5C Changes to equilibrium

STUDY DESIGN DOT POINTS

- the application of Le Chatelier's principle to identify factors that favour the yield of a chemical reaction
- the change in position of equilibrium that can occur when changes in temperature or species or volume (concentration or pressure) are applied to a system at equilibrium, and the representation of these changes using concentration-time graphs

5A 5B 5C 5D

- 3.2.6.1 Le Chatelier's principle
- 3.2.5.1 Effect of adding or removing reactants and products on the position of equilibrium
- 3.2.5.2 Effect of changing volume (pressure) and concentration on the position of equilibrium
- 3.2.5.3 Effect of temperature changes on equilibrium

ESSENTIAL PRIOR KNOWLEDGE

- Concentration

4A Rate of reaction

5A Concentration–time graphs

See questions 40–42.



Image: Rabbitmindphoto/Shutterstock.com

How can six solutions of different colours contain the same three ions?

When the concentration of iron is altered, the equilibrium system shifts to oppose the change in the concentration of iron, causing the solution to change colour. In this lesson, we will learn about how we can use **Le Chatelier's principle** to predict the effect of changing factors such as concentration, pressure and temperature on dynamic equilibrium systems.

KEY TERMS AND DEFINITIONS

Le Chatelier's principle when a system in dynamic equilibrium is subject to a change, the system will adjust itself to partially oppose the effect of the change

Position of equilibrium the relative concentrations of reactants and products at equilibrium for a given chemical reaction

Le Chatelier's principle 3.2.6.1

Le Chatelier's principle describes the behaviour of dynamic equilibrium systems when they are disturbed.

How can the position of equilibrium be changed?

Once a reaction system establishes equilibrium, it will remain in equilibrium until it is disturbed. When it is disturbed, a net reaction will occur, favouring either the forward or reverse reaction to re-establish equilibrium. As we learned in lesson 5B, if a net forward reaction occurs, we say that the **position of equilibrium** has shifted to the right, and if a net reverse reaction occurs, we say that the position of equilibrium has shifted to the left.

Le Chatelier's principle states that when a system in dynamic equilibrium is subjected to a change, the system will adjust itself to partially oppose the effect of the change. We can use this principle as a foundation for understanding the effects of the following factors on closed equilibrium systems:

- Addition or removal of products and/or reactants at a constant volume and temperature.
- Change in volume at constant temperature.
- Change in pressure at constant volume and temperature.
- Change in temperature at constant volume and pressure.

How can we alter the conditions of an equilibrium system for optimum yield?

Using Le Chatelier's principle, we can optimise industrial processes. Famously, in the mass production of ammonia known as the Haber process – which is used extensively in the manufacture of fertilisers – producers will compromise the optimum yield for a faster reaction rate; this will be covered in greater detail in lesson 5D. In industry, the reaction chamber is typically held at around 400 °C and 200 atm, a relatively high temperature and pressure. As we will learn in this lesson, whilst a high pressure is suitable, the required temperature for the optimum yield of ammonia is far lower.

It makes little economical sense, however, to lower the temperature of the chamber and consequently produce ammonia at a much slower rate. Once we have an understanding of the different factors that can disrupt an equilibrium system, we will be able to select conditions for an equilibrium system that allow us to optimise the yield of reactions.

STRATEGY

When a question requires the use of Le Chatelier's principle, it's important to use signposting language in your answer such as 'According to Le Chatelier's principle ...'. Additionally, you should state the full term Le Chatelier's principle instead of abbreviating it to LCP.

USEFUL TIP

Whilst there are several factors that can cause a net reaction to occur in an equilibrium system, only a change in temperature will result in a change in the equilibrium constant (*K*) for a reaction.

PROGRESS QUESTIONS

Question 1

An understanding of Le Chatelier's principle is useful in the chemical industry. A prediction that can be made using this principle is the effect of

A. catalysts on the rate of reaction.

B. catalysts on the position of equilibrium.

C. changes in temperature on the rate of reaction.

D. changes in the concentration of reactants on the position of equilibrium.

VCAA 2019 exam Multiple choice Q1

Effect of adding or removing reactants and products on the position of equilibrium 3.2.5.1

Adding or removing reactants or products will alter their concentrations in the reaction vessel.

How can the addition or removal of reactants or products affect the position of equilibrium?

According to Le Chatelier's principle, if the concentrations of reactants or products in an equilibrium system are changed, the position of the equilibrium will adjust accordingly to minimise the change.[1] The effects of adding/removing reactants/products to an equilibrium system are summarised in table 1.

KEEN TO INVESTIGATE?

[1] **How can six solutions of different colours contain the same three chemicals?**
Search YouTube: Le Chatelier's Principle - Iron(III) Thiocyanate

Table 1 Effect of changes in concentrations on equilibrium

Addition of reactants	Equilibrium favours the forward reaction and shifts to the right to partially oppose the increase in concentration of the reactants.
Removal of reactants	Equilibrium favours the reverse reaction and shifts to the left to partially oppose the decrease in concentration of the reactants.
Addition of products	Equilibrium favours the reverse reaction and shifts to the left to partially oppose the increase in concentration of products.
Removal of products	Equilibrium favours the forward reaction and shifts to the right to partially oppose the decrease in concentration of products.

WORKED EXAMPLE 1

The chemical reaction given below is at equilibrium.

$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$

Using Le Chatelier's principle, explain what happens to the equilibrium position when chlorine, $Cl_2(g)$, is removed from the system at constant volume and temperature.

What information is presented in the question?

An equation for the formation of reactants and products.

The system has a constant volume and temperature.

What is the question asking us to do?

Determine the effect of removing $Cl_2(g)$ on the equilibrium position.

What strategies do we need in order to answer the question?

1. Identify the instantaneous effect of removing $Cl_2(g)$ from the system.
2. Use Le Chatelier's principle to determine in which direction the position of equilibrium will shift.

Answer

Removal of $Cl_2(g)$ will result in an initial decrease in the concentration of $Cl_2(g)$. According to Le Chatelier's principle, the system will favour the forward reaction to partially oppose the decrease in $Cl_2(g)$ concentration. Hence, the position of equilibrium will shift to the right in the direction of the forward reaction.

We can represent the effect of adding or removing reactants or products on an equilibrium system using concentration-time graphs, such as the graph shown in figure 1.

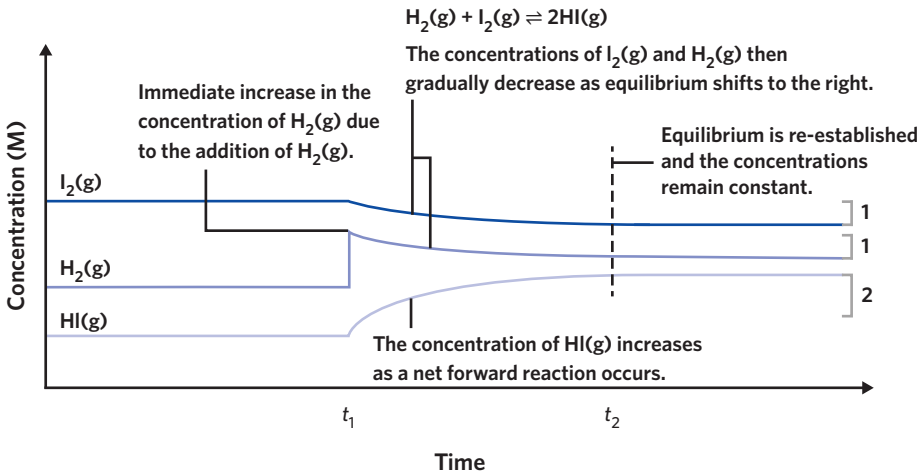


Figure 1 Concentration–time graph representing addition of a reactant

In figure 1, we can see that at time t_1, the concentration of $H_2(g)$ spikes (increases instantaneously), and the concentrations of the other species begin to change gradually.

As per Le Chatelier's principle, the concentration of HI(g) gradually increases, whilst the concentrations of $H_2(g)$ and $I_2(g)$ gradually decrease. This occurs because the system is partially opposing the increase in concentration of $H_2(g)$ by forming more HI(g) until the system re-establishes equilibrium at time t_2.

We can also represent the addition or removal of species using rate-time graphs. In figure 2, for example, we can see that at time t_1, the rate of the forward reaction immediately increases following the addition of $H_2(g)$, but then gradually decreases whilst the rate of the reverse reaction gradually increases. This complies with Le Chatelier's principle as the forward reaction rate spikes due to the addition of a reactant, causing an increase in the rate of the reverse reaction to partially oppose this spike.

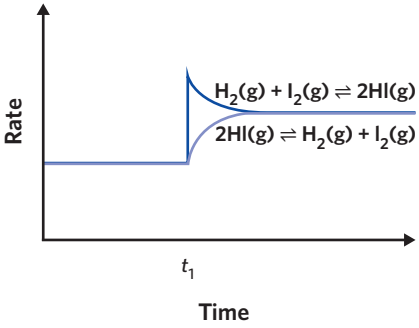


Figure 2 Rate–time graph representing addition of a reactant

USEFUL TIP

In rate-time graphs, the rate of reaction is determined by the rate formula, which uses the concentrations of reactants and products over time to give a quantitative measure of rate. For the purposes of VCE chemistry, it is sufficient to know that addition of reactants causes an immediate spike in the rate of the forward reaction, and addition of products causes an immediate spike in the rate of the reverse reaction.

WORKED EXAMPLE 2

A concentration-time graph for an equilibrium system is shown.

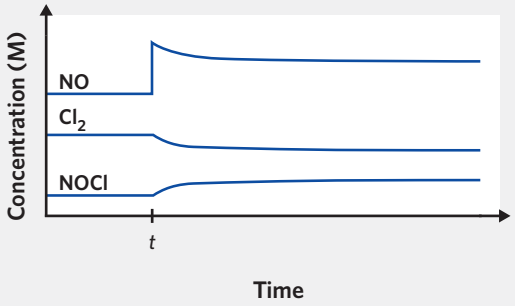
What event occurred at time t to cause the change in equilibrium concentrations?

A. The pressure was decreased at a constant temperature.

B. The temperature was increased at a constant volume.

C. A catalyst was added at a constant temperature and volume.

D. Additional NO gas was added at a constant volume and temperature.



What information is presented in the question?

A concentration-time graph for an equilibrium system

A change in conditions occurred at time t.

What is the question asking us to do?

Determine what change must have occurred at time t to cause the change in concentrations shown in the graph.

What strategy do we need in order to answer the question?

Use the changes in concentration to identify the instantaneous change at time t.

Answer

From the graph, the only instantaneous concentration change at time t was the increase in the [NO].
Hence, NO must have been added to the system, so the correct answer is **option D**.

VCAA 2013 exam Multiple choice Q18

PROGRESS QUESTIONS

Question 2

How does the removal of a product from a system at dynamic equilibrium affect the position of equilibrium?

A. It causes the reverse reaction to stop entirely.

B. It favours the reverse reaction.

C. It favours the forward reaction.

D. It does not affect the position of equilibrium.

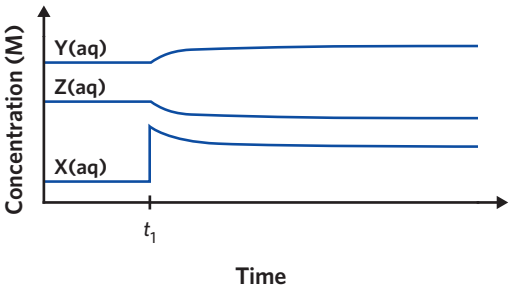
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USEFUL TIP

The use of rate-time graphs to represent changes to equilibrium is not explicitly part of the VCE study design. Nonetheless, questions requiring an understanding of rate-time graphs have been asked in previous VCAA examinations.

Question 3

The concentration-time graph below represents a change to an equilibrium system at time t_1.



Which one of the following would account for the changes in concentration at time t_1?

A. The addition of X(aq)
B. The removal of Y(aq)
C. An increase in temperature
D. A decrease in temperature

Adapted from VCAA 2012 Exam 2 Multiple choice Q7

Effect of changing volume (pressure) and concentration on the position of equilibrium 3.2.5.2

The effect of changing the volume of a reaction vessel on an equilibrium system depends on the type of reaction and the phase (states) of the reactants and products.

How can changing pressure affect equilibrium?

In a gas-phase reaction, changing the volume can affect the pressure of a system, which can in turn affect the position of equilibrium. According to Le Chatelier's principle, when the pressure is increased, the system will shift in the direction that lowers the pressure of the reaction vessel.[2] In terms of stoichiometry, this means the system will shift in the direction that produces fewer moles of gas. By the same token, a decrease in pressure will cause the system to shift in the direction that produces more moles of gas. Consider the reaction provided.

$2NO_2(g) \rightleftharpoons 2NO(g) + O_2(g)$

This reaction produces three moles of gas from two moles of reactants. If the volume of the container is decreased, the pressure will increase, causing the system to shift in the direction that produces fewer moles of gas, which in this case is to the left, favouring the reverse reaction.

Similarly, if the volume of the container is increased, the pressure will decrease, causing the system to shift in the direction that produces more moles of gas, which in this case is to the right, favouring the forward reaction.

KEEN TO INVESTIGATE?

[2] **How is the colour of gas affected by changes in volume?**
Search YouTube: Volume Effect on Equilibrium - Le Chatelier's Principle Lab Extension

USEFUL TIP

Pressure and volume are inversely proportional; this means that when pressure decreases, volume increases, and when pressure increases, volume decreases.

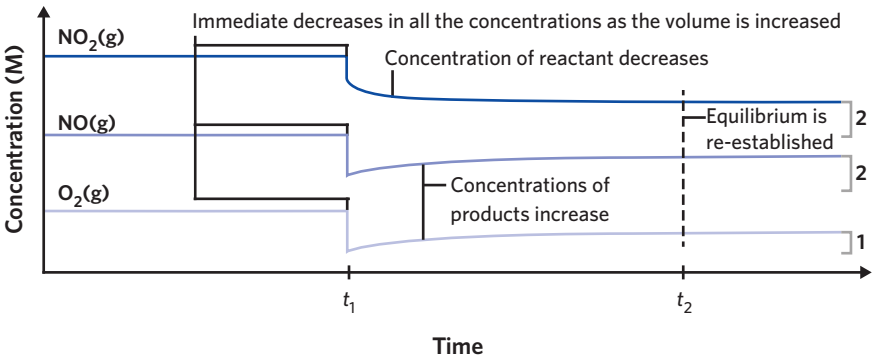


Figure 3 Concentration–time graph representing an increase in the volume of the reaction vessel

In figure 3, we can see an immediate decrease in the concentrations of all species present. From this, we can deduce that an increase in volume has occurred, as that is the only change that results in an immediate decrease in concentration of all species. Since the volume has increased, the pressure has decreased. Therefore, in order to partially oppose the decrease in pressure, the system attempts to re-establish equilibrium by favouring the reaction that produces more moles of gas particles, which in this case is the forward reaction.

WORKED EXAMPLE 3

Consider the equation for the steam reforming process shown below.

$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \quad \Delta H = +207$ kJ

According to Le Chatelier's principle, the forward reaction will be favoured if

A. the pressure is increased.

B. the pressure is decreased.

C. $H_2O(g)$ is removed from the reaction vessel.

D. the volume of the reaction vessel is decreased.

What information is presented in the question?

The equation for the steam reforming process.

What is the question asking us to do?

Determine which of the options will result in the forward reaction being favoured.

What strategies do we need in order to answer the question?

1. Recall the effect of pressure changes on the position of equilibrium.
2. Recall the effect of removing reactants on the position of equilibrium.
3. Recall the effect of changes in volume on the pressure of the reaction vessel.

Answer

Option A: If the pressure is increased, then by Le Chatelier's principle, the system will favour the reaction that produces the fewest particles of gas, which is the reverse reaction, in order to partially oppose the increase in pressure. Therefore, option A is incorrect.

Option B: If the pressure is decreased, then by Le Chatelier's principle, the system will favour the reaction that produces the most particles of gas, which is the forward reaction, in order to partially oppose the decrease in pressure. Therefore, option B is correct.

Option C: If $H_2O(g)$ is removed from the reaction vessel, then by Le Chatelier's principle, the system will favour the reverse reaction, producing more $H_2O(g)$ in order to partially oppose the decrease in the $[H_2O(g)]$. Therefore option C is incorrect.

Option D: If the volume of the reaction vessel is decreased, then the pressure of the system is increased. Following the same logic as in option A, option D must also be incorrect.

Adapted from VCAA 2010 exam 2 Short answer Q1aii

How can changing concentration affect the position of equilibrium?

So far, we have explored the effects of adding or removing reactants and/or products on the position of equilibrium. This is one way that the concentration of species can be altered to affect equilibrium. For equilibrium systems in solution, dilutions can also affect the proportion of reactants and products in an equilibrium system, in turn affecting the position of equilibrium.

If water is added to an aqueous mixture at equilibrium, thereby diluting it, the concentrations of all species will decrease. In a similar manner to gas-phase equilibria, by Le Chatelier's principle, the system will favour the reaction that produces the most particles in order to partially oppose the decreased concentrations. Consider the reaction below.

$CoCl_4^{2-}(aq) \rightleftharpoons Co^{2+}(aq) + 4Cl^-(aq)$

blue pink

If a blue solution containing $CoCl_4^{2-}(aq)$, $Co^{2+}(aq)$, and $Cl^-(aq)$ was diluted, the concentrations of all species would instantaneously decrease. Hence, to partially oppose this, the system would favour the forward reaction in order to produce a greater number of particles (1 particle ⇌ 5 particles), thereby changing the colour of the solution to pink.

WORKED EXAMPLE 4

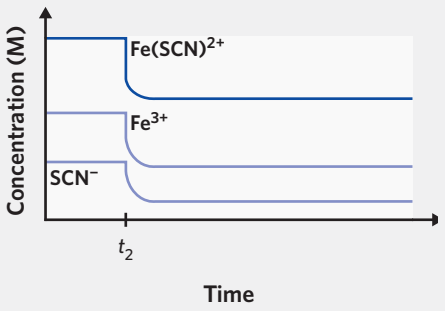
Consider the equilibrium system represented by the equation below.

$Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons Fe(SCN)^{2+}(aq)$

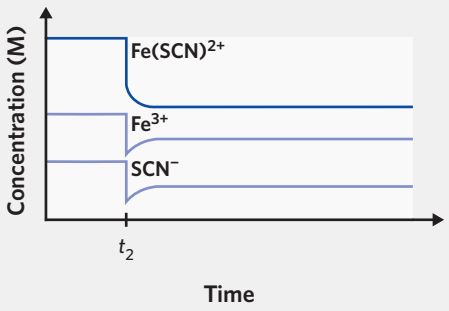
yellow deep red

Which one of the following best represents the changes in concentration when the equilibrium mixture is diluted at time t_2?

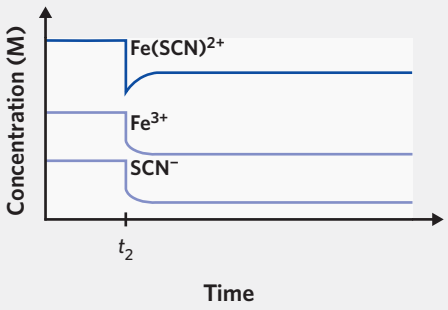
A.



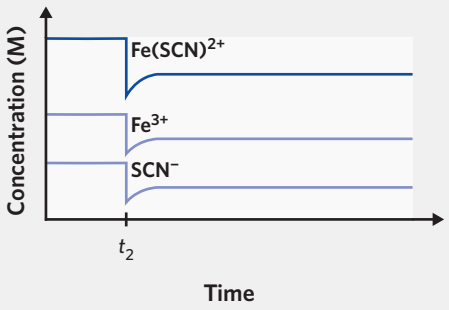
B.



C.



D.



What information is presented in the question?

An equation for an equilibrium system.

Four different concentration–time graphs representing the changes following dilution at time t_2.

What is the question asking us to do?

Determine which of the graphs accurately represents the effect of dilution on the equilibrium system.

What strategies do we need in order to answer the question?

1. Recall the instantaneous effect of dilution on the equilibrium system.
2. Use Le Chatelier's principle to determine the direction in which the equilibrium position will shift as a result of the dilution.
3. Determine which graph accurately represents both the changes at time t_2 and the changes after time t_2.

Answer

Upon dilution, the concentrations of $Fe^{3+}(aq)$, $SCN^-(aq)$ and $Fe(SCN)^{2+}(aq)$ all instantaneously decrease. By Le Chatelier's principle, the system will respond to partially oppose this instantaneous decrease in 'total' concentration by favouring the reaction direction that produces more particles.

$Fe^{3+}(aq) + SCN^-(aq) \rightleftharpoons Fe(SCN)^{2+}(aq)$

From the equation, we can see that more particles are produced by favouring the reverse reaction, so the equilibrium system will shift to the left. As a result, the $[Fe(SCN)^{2+}]$ will continue to decrease as the $[Fe^{3+}]$ and $[SCN^-]$ both increase.

Hence, the graph that aligns with all of these expected outcomes is the graph given in **option B**.

Adapted from VCAA 2012 Exam 2 Multiple choice Q8

Why are some equilibrium systems not affected by changes to pressure or concentration?

If there is an equal number of particles on both sides of an equation, then a change in volume or a dilution will have no effect on equilibrium. This is because favouring neither the forward nor reverse reactions would affect the number of particles in the system. Therefore, any equilibrium shift would be unable to partially oppose changes to factors such as pressure or concentration. For example, consider the reaction below.

$Br_2(g) + Cl_2(g) \rightleftharpoons 2BrCl(g)$

As shown in figure 4, a decrease in volume is applied to a system at equilibrium at time t_1, thereby increasing the pressure of the system. Since 2 moles of gas react to produce 2 moles of gas, a shift in either direction will have no effect on the pressure of the system. Although the overall concentrations and rates of reaction have changed, they do so in proportion to their relative mole ratios, meaning the position of equilibrium and the value of K remain unchanged.

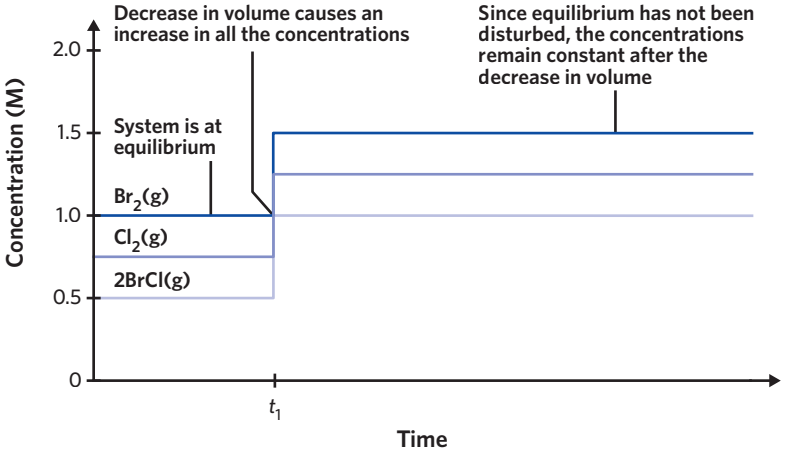


Figure 4 Concentration–time graph representing a decrease in the volume of the reaction vessel

MISCONCEPTION

'The value of K will not change if all the concentrations are halved.'

If only one chemical is changed the system will shift accordingly to minimise the change and restore K, however, if all the concentrations are changed at once (at a constant volume and temperature) a new K value will be produced.

WORKED EXAMPLE 5

Consider the equation given below.

$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$

The concentrations of each substance in a mixture at dynamic equilibrium are given below.

Substance	Concentration (M)
$CO(g)$	1.0
$H_2O(g)$	2.0
$CO_2(g)$	2.0
$H_2(g)$	1.5

The volume of the reaction vessel is then doubled at a time t_1. Draw a concentration–time graph representing the effect of this change in volume.

What information is presented in the question?

The equation for an equilibrium system.

The concentrations of each substance at equilibrium.

The volume of the reaction vessel is doubled.

What is the question asking us to do?

Draw a concentration–time graph representing the changes in concentration when the volume of the reaction vessel is doubled.

Continues →

What strategies do we need in order to answer the question?

1. Recall the relationship between changes in volume and changes in concentration.
2. Recall the effect of a change in concentration on the position of equilibrium.

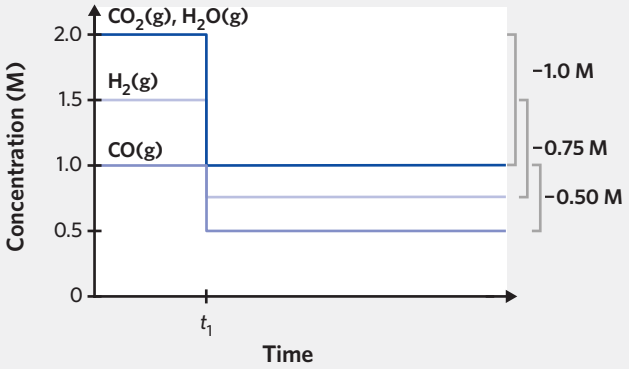
Answer

According to the formula $n = c \times V$, volume and concentration are inversely proportional, so when the volume is doubled, the concentration of each substance will be halved. Hence, the concentrations of each substance at time t_1 will be:

Substance	Concentration (M)
$CO(g)$	$\frac{1}{2} \times 1.0\ M = 0.50\ M$
$H_2O(g)$	$\frac{1}{2} \times 2.0\ M = 1.0\ M$
$CO_2(g)$	$\frac{1}{2} \times 2.0\ M = 1.0\ M$
$H_2(g)$	$\frac{1}{2} \times 1.5\ M = 0.75\ M$

When the volume of the reaction vessel is increased, the pressure of the reaction vessel will decrease. By Le Chatelier's principle, the system will then shift to favour the reaction that produces more particles. However, in the reaction $CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$, both the forward and reverse reactions produce two particles of gas. Therefore, favouring either reaction will have no effect on the pressure of the system, meaning there will be no shift in the position of equilibrium.

Hence, we can draw our concentration–time graph as shown.



The addition of an inert (unreactive) gas such as argon or helium to a reaction vessel also has no effect on the position of equilibrium. The explanation for this phenomenon involves an understanding of partial pressures, which is content that goes beyond the scope of the study design.

WORKED EXAMPLE 6

The following equation represents a system that has reached dynamic equilibrium.

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \quad \Delta H = -197\ kJ$

Argon gas is then added at constant volume and temperature. Explain what will happen to the concentration of oxygen gas.

What information is presented in the question?

An equation representing an equilibrium system.

Argon gas is added to the system at constant volume and temperature.

What is the question asking us to do?

Determine the change, if any, in the concentration of oxygen gas.

What strategy do we need in order to answer the question?

Determine the effect of adding an inert gas on the position of equilibrium.

Answer

The addition of an inert gas has no effect on the position of equilibrium, and thus, the concentration of oxygen gas will not change.

PROGRESS QUESTIONS

Question 4

Which of the following statements is true regarding the effect of changing the pressure on a system in dynamic equilibrium?

A. Decreasing the pressure may cause the system to favour the reaction that produces fewer moles of gas.

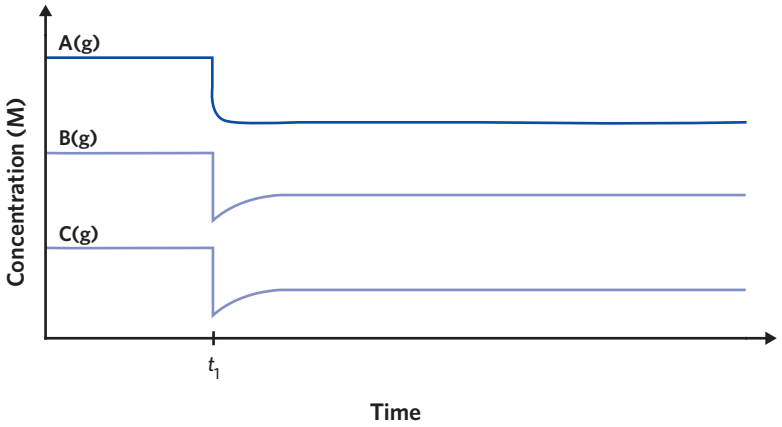
B. Increasing the pressure may cause the system to favour the reaction that produces fewer moles of gas.

C. Increasing the pressure may cause the system to favour the reaction that produces more moles of gas.

D. Changing the pressure will never have any effect on the position of equilibrium.

Question 5

Which of the following changes would explain the change at time t_1 in the graph shown?



A. An increase in the volume of the reaction vessel at constant temperature

B. A decrease in the volume of the reaction vessel at constant temperature

C. Removal of B(g) at constant volume and temperature

D. An increase in temperature at constant volume

Question 6

Hydrogen is produced on an industrial scale from methane. The equation for the reaction is

$$2H_2O(g) + CH_4(g) \rightleftharpoons CO_2(g) + 4H_2(g)$$

If an inert gas is added to an equilibrium system at a constant temperature and a constant volume, the concentration of hydrogen will

A. increase.

B. decrease.

C. not change.

D. decrease then increase.

VCAA 2014 exam Multiple choice Q2

Effect of temperature changes on equilibrium 3.2.5.3

When a change in temperature occurs at a constant volume and pressure, the position of equilibrium will shift according to the enthalpy change of the forward and reverse reactions.

How can changing temperature affect both the position of equilibrium and the value of *K*?

Unlike any other factor, a change in temperature also changes the value of the equilibrium constant *K*. The effect of temperature changes on the value of the equilibrium constant are summarised in table 2.

Table 2 Effect of temperature changes on an equilibrium system

ΔH	Temperature change	Equilibrium shifts to the:	Effect on *K*
Exothermic	Increase	left	Decrease
Exothermic	Decrease	right	Increase
Endothermic	Increase	right	Increase
Endothermic	Decrease	left	Decrease

STRATEGY

To remember the effect of changes in temperature on equilibrium systems, it can be useful to think of heat as a reactant/product. For example, an exothermic reaction releases heat and therefore has heat on the right-hand side of the equation. If the temperature is decreased, heat is being removed from the system. By Le Chatelier's principle, the system will move to partially oppose this removal of heat by favouring the forward reaction, thereby adding more heat.

If the temperature of an equilibrium system is increased, there is more energy available to the system. As a result, the endothermic (heat-absorbing) reaction is favoured to partially oppose the increase in heat energy. On the contrary, if the temperature is decreased, the exothermic (heat-releasing) reaction will be favoured to partially oppose this decrease. Consider the following reaction.

$$CO(g) + Cl_2(g) \rightleftharpoons COCl_2(g) \quad \Delta H > 0$$

We can see that the reaction is endothermic as the change in enthalpy is positive. Hence, if the temperature at which this reaction occurred was increased, the forward reaction would be favoured to absorb the increased heat energy. Hence, as we learned in lesson 5B, the proportion of reactants that have formed products will increase, and thus, the value of *K* will increase. This scenario is represented in the concentration-time graph in figure 5.

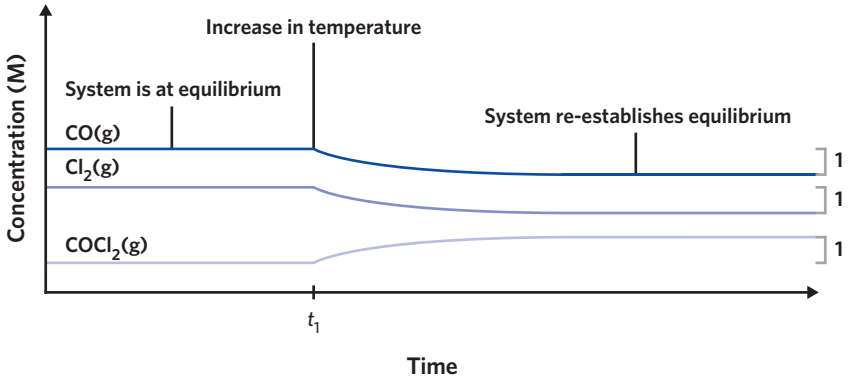


Figure 5 Concentration–time graph representing an increase in temperature

WORKED EXAMPLE 7

The following concentration-time graph refers to a mixture of three gases, P, Q, and R, in an enclosed 5.0 L container. At time t_1 the mixture is heated.

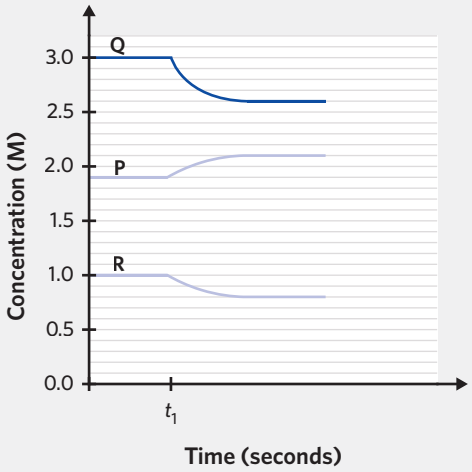
The equilibrium system that represents the graph is

A. $P(g) \rightleftharpoons 2Q(g) + R(g)$ and the forward reaction is exothermic.

B. $2Q(g) \rightleftharpoons P(g) + R(g)$ and the forward reaction is endothermic.

C. $2Q(g) + R(g) \rightleftharpoons P(g)$ and the forward reaction is exothermic.

D. $P(g) + 2Q(g) \rightleftharpoons R(g)$ and the forward reaction is endothermic.



What information is presented in the question?

A concentration-time graph for a mixture of three gases P, Q and R in a 5.0 L closed container.

The mixture is heated at time t_1.

What is the question asking us to do?

Determine the correct equation represented by the graph.

Determine whether the forward reaction is endothermic or exothermic.

What strategies do we need in order to answer the question?

1. Determine which substance is increasing in concentration.
2. Recall the effect of increasing temperature on the position of equilibrium for endothermic and exothermic reactions.
3. Determine the proportion with which the concentrations of each species change.

Answer

Since the concentration of P increases as a result of the temperature increase, it must be produced when the equilibrium mixture is heated, whilst Q and R, which both decrease in concentration, must be consumed. Hence, the reaction that produces P must be endothermic.

The change in concentration of Q is twice the changes in concentrations of P and R, and hence the favoured reaction is

$2Q(g) + R(g) \rightarrow P(g) \quad \Delta H > 0$

Therefore, **option A** is the correct answer as for $P(g) \rightleftharpoons 2Q(g) + R(g)$, an exothermic forward reaction results in an endothermic reverse reaction for the production of P.

Adapted from VCAA 2019 exam Multiple choice Q25

PROGRESS QUESTIONS

Question 7

The temperature of an equilibrium system with an endothermic forward reaction is increased. The value of K

A. will increase and the equilibrium position will shift to the right.

B. will decrease and the equilibrium position will shift to the right.

C. will increase and the equilibrium position will shift to the left.

D. will decrease and the equilibrium position will shift to the left.

Continues →

Question 8

Ammonia, NH_3, can be produced by the reaction of hydrogen, H_2, and nitrogen, N_2. When this reaction takes place in a sealed container of fixed volume, an equilibrium system is established. The equation for the reaction is shown below.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92$ kJ

If the pressure and volume remain constant when the temperature is increased, the forward reaction rate will

A. increase and the $[NH_3]$ will increase.

B. increase and the $[NH_3]$ will decrease.

C. decrease and the $[NH_3]$ will decrease.

D. decrease and the $[NH_3]$ will remain the same.

VCAA 2017 exam Multiple choice Q18

Theory summary

- Le Chatelier's principle states that when a system in dynamic equilibrium is subjected to a change, the system will adjust itself to partially oppose the effect of the change.
- Effects of changes in concentrations on equilibrium:

Addition of reactants	Forward reaction is favoured
Removal of reactants	Reverse reaction is favoured
Addition of products	Reverse reaction is favoured
Removal of products	Forward reaction is favoured

- Effects of changes in pressure and volume on equilibrium:

Increase in pressure	System favours the reaction that produces fewer moles of gas
Decrease in pressure	System favours the reaction that produces more moles of gas
Increase in volume	System favours the reaction that produces more moles of gas
Decrease in volume	System favours the reaction that produces fewer moles of gas

- When a solution in dynamic equilibrium is diluted, the system will favour the reaction that produces more particles.
- Cases in which the position of equilibrium does not change:
  - When the forward and reverse reactions in an equilibrium system produce the same number of particles.
  - When an inert gas is added to a gaseous equilibrium system.
- Effect of temperature changes on an equilibrium system:

ΔH	Temperature change	Equilibrium favours the:	Effect on K
Exothermic	Increase	reverse reaction	Decrease
Exothermic	Decrease	forward reaction	Increase
Endothermic	Increase	forward reaction	Increase
Endothermic	Decrease	reverse reaction	Decrease

- The only factor that can cause the value of K to change is a change in temperature.

5C Questions

Mild Medium Spicy

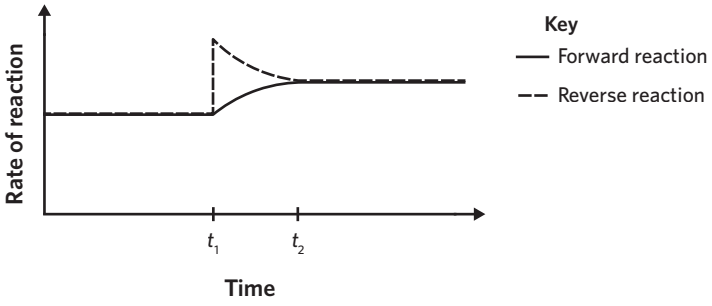
Deconstructed

Use the following information to answer questions 9–11.

An equilibrium mixture of four gases is represented by the following equation.

$A(g) + 2B(g) \rightleftharpoons C(g) + D(g) \quad \Delta H > 0$

The graph below shows the rate of the forward and reverse reactions versus time. A single change is made to the equilibrium mixture at time t_1 and equilibrium is re–established at time t_2.



Question 9 (1 MARK)

Which of the following changes could have occurred at time t_1?

A. Addition of A(g)

B. Addition of C(g)

C. A decrease in temperature

D. An Increase in temperature

Question 10 (1 MARK)

Just after time t_1, the _____ reaction is favoured and the [B(g)] is _____.

A. forward, increasing

B. forward, decreasing

C. reverse, increasing

D. reverse, decreasing

Question 11 (1 MARK)

Which one of the following is consistent with the information given above?

A. Argon is added to the equilibrium mixture at time t_1.

B. At time t_1 reactants are removed from the equilibrium mixture.

C. The amount of products is higher at time t_2 compared to just before time t_1.

D. The change made at time t_1 results in an increase in the equilibrium constant at time t_2.

VCAA 2021 exam Multiple choice Q25

Exam-style

Question 12 (4 MARKS)

The following equation represents a gaseous reaction that takes place in a sealed container.

$4NH_3(g) + 3O_2(g) \rightleftharpoons 2N_2(g) + 6H_2O(g) \quad \Delta H < 0$

The temperature of the reaction system is increased and a new equilibrium is established. How does the increase in the temperature affect the value of the equilibrium constant? Justify your answer.

VCAA 2022 exam Short answer Q3bi

Question 13 (1 MARK)

Chromate, CrO_4^{2-}, and dichromate, $Cr_2O_7^{2-}$, ions in solution reach equilibrium as shown in the following equation.

$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$

To increase the concentration of CrO_4^{2-} in a solution at equilibrium, a student could add a few drops of

A. H_2O

B. 1 M HCl

C. 1 M NaCl

D. 1 M NaOH

Adapted from VCAA (NHT) 2019 exam Multiple choice Q21

Question 14 (1 MARK)

Dissolved carbon dioxide, CO_2, can react with water, H_2O, to form carbonic acid, H_2CO_3. Carbonic acid can also react with H_2O to form bicarbonate ions, HCO_3^-, and hydronium ions, H_3O^+.

$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$

$H_2CO_3(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + H_3O^+(aq)$

A beaker that contains 2 L of deionised water is placed in a room and left overnight so that these two reactions reach equilibrium. In the morning, one change is made to the system. Which one of the following changes is most likely to result in an increase in the concentration of H_3O^+ ions?

A. Diluting the solution

B. Bubbling in more CO_2 gas

C. Adding a few drops of phenolphthalein indicator

D. Adding a few drops of 0.1 M sodium hydroxide, NaOH, solution

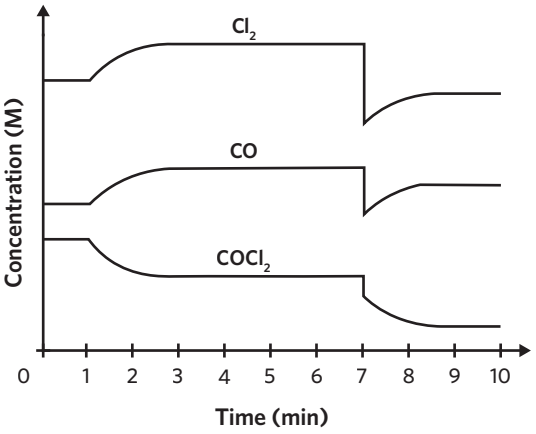
VCAA (NHT) 2018 exam Multiple choice Q28

Question 15 (1 MARK)

The following equation represents the reaction between chlorine gas, Cl_2, and carbon monoxide gas, CO.

$Cl_2(g) + CO(g) \rightleftharpoons COCl_2(g) \quad \Delta H = -108 \text{ kJ mol}^{-1}$

The concentration–time graph below represents changes to the system.



Which of the following identifies the changes to the system that took place at 1 minute and at 7 minutes?

	1 minute	7 minutes
A.	Increase in temperature	Increase in volume
B.	Decrease in temperature	Decrease in volume
C.	Decrease in temperature	Increase in volume
D.	Increase in temperature	Decrease in volume

VCAA 2020 exam Multiple choice Q17

Question 16 (8 MARKS)

The main reaction in methanol production from biogas is represented by the following equation.

$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \quad \Delta H < 0$

a. In industry, Le Chatelier's principle is employed to optimise the yield of methanol from biogas. Explain the effect of the following factors on the yield of methanol. Refer to Le Chatelier's principle in each answer.

i. Reaction temperature 2 MARKS

ii. Reaction pressure 2 MARKS

b. Write the expression for the equilibrium constant, K, for this reaction. 1 MARK

c. 0.760 mol of carbon monoxide, CO, and 0.525 mol of hydrogen, H_2, were allowed to reach equilibrium in a 500 mL container. At equilibrium the mixture contained 0.122 mol of methanol. Calculate the equilibrium constant, K. 3 MARKS

Adapted from VCAA 2020 exam Short answer Q1b, c, d

Question 17 (2 MARKS)

Hydrogen sulfide, in solution, is a diprotic acid and ionises in two stages.

(1) $H_2S(aq) + H_2O(l) \rightleftharpoons HS^-(aq) + H_3O^+(aq)$

(2) $HS^-(aq) + H_2O(l) \rightleftharpoons S^{2-}(aq) + H_3O^+(aq)$

Some solid sodium hydrogen sulfide, NaHS, is added to a 0.01 M solution of H_2S. Predict the effect of this addition on the pH of the hydrogen sulfide solution. Justify your prediction.

Adapted from VCAA 2015 exam Short answer Q8c

Key science skills

Question 18 (12 MARKS)

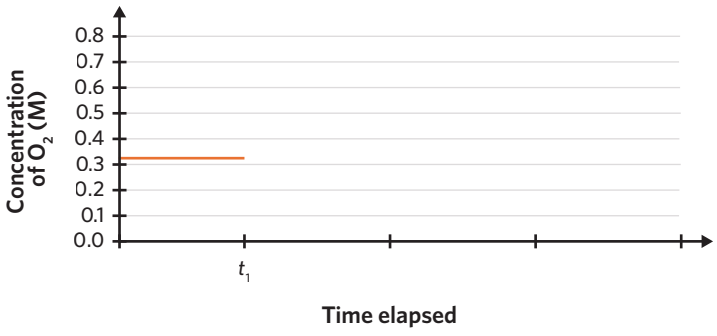
5.0 mol of oxygen, O_2, and 10.0 mol of sulfur dioxide, SO_2, are injected into a 5.0 L evacuated and sealed container at standard laboratory conditions (SLC) and allowed to achieve equilibrium. The equation for this reaction is given below.

$O_2(g) + 2SO_2(g) \rightleftharpoons 2SO_3(g) \quad \Delta H = -196 \text{ kJ}$

a. At equilibrium, the concentration of O_2 is 0.32 M. Calculate the equilibrium constant, K. 3 MARKS

b. At time t_1 after equilibrium has been achieved, the volume of the container is expanded to 10.0 L at constant temperature.

i. On a graph similar to the one provided, draw the concentration of O_2 after time t_1 until equilibrium is re-established. 2 MARKS



ii. Justify your answer to part **b.i** using Le Chatelier's principle. 2 MARKS

c. The equation given above represents a key reaction that occurs in the contact process for the production of sulfuric acid. The reaction conditions used by three different companies to produce sulfur trioxide are given in the table below.

Reaction condition	Company 1	Company 2	Company 3
Temperature	High	Low	High
Pressure	High	High	Low

i. Which of the three companies is likely to generate the highest percentage yield of sulfur trioxide? Justify your answer. 3 MARKS

ii. Identify the economic impact of the conditions used by Company 1. 1 MARK

iii. Identify the key environmental concern associated with this step in the contact process. 1 MARK

Adapted from VCAA (NHT) 2021 exam Short answer Q6a, b

FROM LESSONS 12B, 12C & 12E

Questions from multiple lessons

Question 19 (14 MARKS)

The industrial production of hydrogen involves the following two reactions.

(1) $CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \quad \Delta H = +206$ kJ

(2) $CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g) \quad \Delta H = -41$ kJ

a. Write 'increase', 'decrease' or 'no change' in a table similar to the one below to identify the expected effect of each change to reaction 1 and reaction 2 on the yield of hydrogen. 3 MARKS

Change to reaction 1 and 2	Effect of the change on the yield of H_2	
	Reaction 1	Reaction 2
Addition of steam at a constant volume and temperature		
Increase in temperature at a constant volume		
Addition of a suitable catalyst at a constant volume and temperature		

b. Explain the effect of decreasing the volume, at constant temperature, on the hydrogen equilibrium yield in each reaction.

i. Reaction 1 2 MARKS

ii. Reaction 2 2 MARKS

c. What is the effect of an increase in temperature at constant volume on the rate of hydrogen production in each reaction?

i. Reaction 1 1 MARK

ii. Reaction 2 1 MARK

d. The reaction between hydrogen and oxygen is the basis of energy production in a number of fuel cells.

$2H_2(g) + O_2(g) \rightleftharpoons 2H_2O(l) \quad \Delta H = -571.6$ kJ

An alkaline electrolyte is used in a particular hydrogen/oxygen fuel cell. Write a balanced half-equation for the reaction occurring at the

i. cathode. 1 MARK

ii. anode. 1 MARK

e. What is the maximum voltage predicted for one alkaline hydrogen/oxygen fuel cell under standard conditions? 1 MARK

f. Much of the hydrogen used in fuel cells is produced from methane.

$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g)$

$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$

Explain why methane generated by biomass is a renewable fuel, whilst methane derived from fossil fuels is not. 2 MARKS

Adapted from VCAA 2013 exam Short answer Q4

FROM LESSONS 1B, 3D, 3E & 4A

Back to contents

5D Compromise conditions


Image: Alchemist from India/Shutterstock.com

How can we decarbonise the mass production of fertilisers?

The use of **green hydrogen** in the production of ammonia, the key ingredient in the manufacture of fertilisers, is integral to reducing the carbon footprint of the Haber-Bosch process. In this lesson, we will employ green chemistry principles to explore how catalysts and energy-efficient processes can help chemists find the most economic yield of equilibrium reaction products.

KEY TERMS AND DEFINITIONS

Compromise conditions conditions that may not always give the greatest yield of product, but are the most economically viable when it comes to balancing factors like cost and rate of reaction

Decarbonisation the process of reducing or eliminating carbon dioxide and other greenhouse gas emissions from industrial processes

Green hydrogen hydrogen gas produced using renewable energy sources, such as wind or solar power, through electrolysis

Grey hydrogen hydrogen gas produced through steam methane reforming (SMR), a process that involves reacting natural gas with steam to produce hydrogen gas and carbon dioxide as a by-product

Side reaction a reaction that occurs at the same time as the main reaction, leading to the formation of side products and a lower yield of the main product

STUDY DESIGN DOT POINT

- responses to the conflict between optimal rate and temperature considerations in producing equilibrium reaction products, with reference to the green chemistry principles of catalysis and designing for energy efficiency

5A 5B 5C 5D

3.2.9.1 & 3.2.9.2 Green chemistry principles – part 2 & catalysis and equilibrium

3.2.9.1 & 3.2.9.3 Green chemistry principles – part 2 & designing for energy efficiency

ESSENTIAL PRIOR KNOWLEDGE

4B Catalysts

5C Le Chatelier's principle

See questions 43–44.

Green chemistry principles – part 2 & catalysis and equilibrium 3.2.9.1 & 3.2.9.2

The conflict between optimal rate and optimal yield is often navigated through the principles of equilibrium systems.

How is Le Chatelier's principle used to optimise the yield of equilibrium reactions?

As we learned in lesson 5C, Le Chatelier's principle can be used to predict the effect of changes to an equilibrium system on the position of equilibrium. In industry, this principle is used to find the ideal conditions for producing equilibrium reaction products.

Consider the equation for the production of ammonia in the Haber-Bosch process.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H < 0$

This equation represents the equilibrium system formed when nitrogen and hydrogen gas are allowed to react. Using Le Chatelier's principle, the ideal conditions for obtaining the optimal yield of ammonia are high pressure and low temperature (figure 1).

USEFUL TIP

Since industrial processes often require extremely high pressures, on graphs like figure 1 the pressure will often be given in megapascals (MPa), which is equivalent to 10^6 pascals. This conversion can be found using the VCE Data Book.

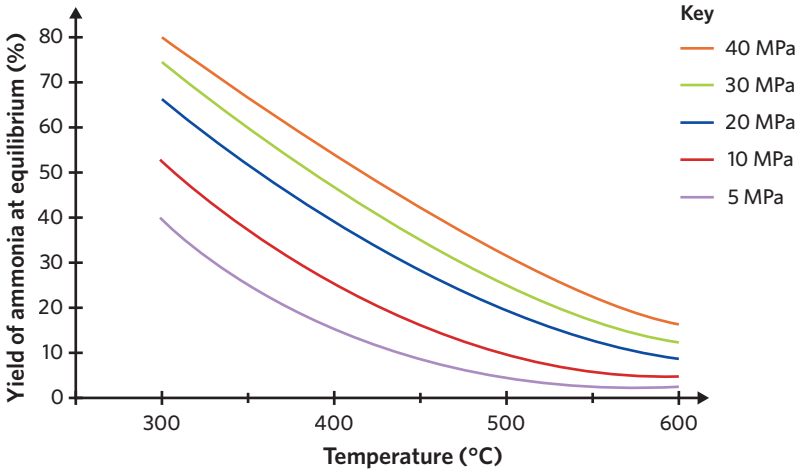


Figure 1 Effect of temperature and pressure on the percentage yield of ammonia at equilibrium

Despite often lowering the overall yield of desired products, many industrial processes will use high temperatures due to the economic benefits associated with the increased rate of reaction. Altered reaction conditions that provide the best balance between yield and rate are known as **compromise conditions**. For example, in the Haber process, a temperature of 450 °C is used as the lower yield is offset by the faster rate with respect to economic considerations.

How are catalysts used to optimise the formation of reaction products?

MISCONCEPTION

'Catalysts affect the yield of a reaction.'

As we learned in lesson 4B, catalysts only affect the rate, they do not affect the yield of the reaction. A catalysed reaction produces the same amount of product as an uncatalysed reaction but it produces the product at a faster rate.

As we learned in lesson 4A, most chemical reactions occur more quickly at higher temperatures. Since the yield of ammonia from the Haber-Bosch process is greatest at lower temperatures, a conflict arises. In industry, this conflict can be resolved using catalysts, which can increase the rate of ammonia production.

In the Haber-Bosch process, there are typically four crystalline catalyst beds (figure 2), each of which consists of finely divided iron bound to an iron oxide support (figure 3). Within the iron oxide support, there are promoters such as aluminium oxide and potassium oxide which prevent the catalyst from clumping by absorbing any water vapour formed.

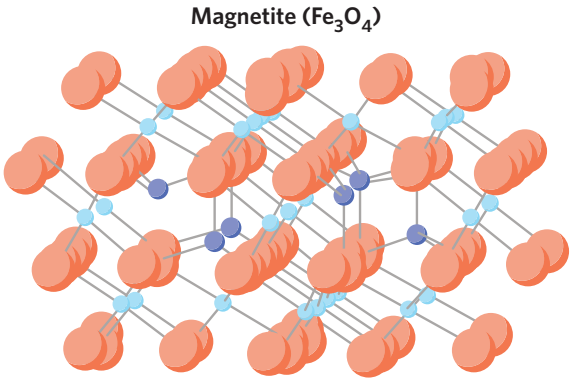


Figure 2 The large internal surface area of crystalline catalysts allows gases to pass through easily.

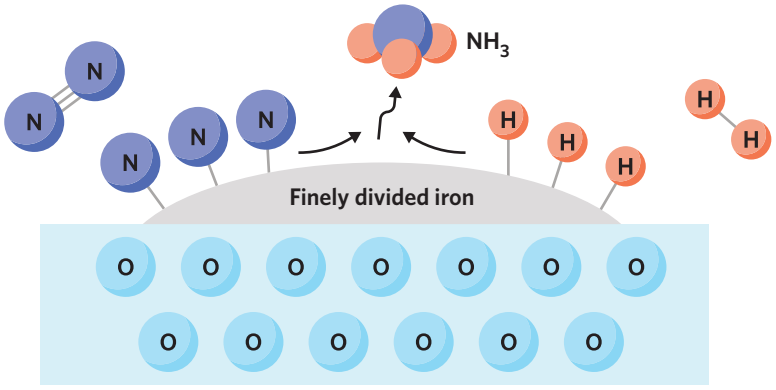


Figure 3 Catalyst bed used in the Haber-Bosch process

This combination of iron powder and promoters enable the gas particles to pass through the catalyst beds, reducing the activation energy by as much as 30 kJ. The purpose of this reduction in activation energy is two-fold: it increases the rate of the reaction and reduces the energy input required, thereby making the wwHaber-Bosch process more energy efficient.

Whilst the promoters slow down the clumping of the catalyst beds, there is still an eventual need for the iron catalyst to be replaced. To prevent wastage, the clumped iron is typically reduced back into iron powder to be reused again.

Another example of sustainable catalysis is the recycling of catalytic converters. Catalytic converters are used in cars to convert toxic gases released from a combustion engine into less toxic pollutants. The catalyst is a ceramic honeycomb structure (figure 4), coated with a mixture of precious metals such as palladium and rhodium.



Image: Aleksandr Kondratov/Shutterstock.com

Figure 4 The honeycomb structure of a catalytic converter can have a surface area of up to 500 m^2.

MISCONCEPTION

'When a catalyst needs to be replaced, it has been used up in a reaction.'

Catalysts are not used up in the reactions they catalyse, meaning they do not undergo chemical changes. They do, however, undergo physical changes that necessitate replacing or refining the catalysts.

The various platinum–group metals used in catalytic converters – like palladium – are difficult to mine, requiring significant energy and large amounts of ore. Fortunately, modern technology allows for over 95% of platinum-group metals used in catalytic converters to be refined and reused.[1] Hence, the recycling of catalysts serves to both preserve the Earth's finite resources, and to reduce the amount of waste sent to landfills.

KEEN TO INVESTIGATE?

[1] **How are the precious metals in catalytic converters recycled**
Search YouTube: Recycling Factories – Precious Metals Extraction of Catalytic Converters

How can the formation of unwanted side products be reduced using catalysts?

Whilst higher temperatures cause an equilibrium system to favour the endothermic reaction, they also increase the risk of **side reactions** occuring. Side reactions are typically unwanted reactions that occur at the same time as the main reaction, leading to the formation of side products and reducing the yield of the desired product.

Consider the following equation for the catalytic oxidation of ethene to produce epoxyethane.

$$2C_2H_4(g) + O_2(g) \rightarrow 2C_2H_4O(g)$$

Ethene can also combust in the presence of oxygen to produce carbon dioxide and water vapour.

$$C_2H_4(g) + 3O_2(g) \rightarrow 2CO_2(g) + 2H_2O(g)$$

USEFUL TIP

The selectivity of a catalyst refers to how unique its catalytic activity is. A catalyst that increases the rate of many reactions is less selective than a catalyst that affects only one reaction.

In this scenario, when the temperature of the reaction system increases, both reactions occur more quickly. Since the side reaction is irreversible, when C_2H_4 oxidises, unwanted CO_2 and H_2O are produced and cannot be converted back into C_2H_4. By using a small amount of 1,2-dichloroethane, the formation of epoxyethane can be selectively catalysed using finely divided silver on an inert support such as alumina, reducing the formation of unwanted products, thereby improving the efficiency of the manufacturing process.

Unwanted side products can destroy production equipment, such as by building up on the internal walls of pipes, limiting the flow of reactants or products. Hence, by using catalysts instead of high temperatures, the lifetime of equipment used in industrial processes can be extended, meaning the wastage of equipment is dramatically reduced.

WORKED EXAMPLE 1

In industrial processes, the key factors that determine the percentage yield of an equilibrium reaction product are

A. temperature and the use of catalysts.

B. pressure and the use of catalysts.

C. temperature and pressure.

D. None of the above

What information is presented in the question?

The possible factors that determine the percentage yield of an equilibrium reaction product.

What is the question asking us to do?

Determine which pair of factors affects the percentage yield of an equilibrium reaction product.

What strategies do we need in order to answer the question?

1. Recall the effect of temperature on percentage yield.
2. Recall that catalysts have no effect on percentage yield.
3. Recall the effect of pressure on percentage yield.

Answer

According to Le Chatelier's principle, equilibrium systems will respond to changes in temperature by shifting in either the forward or reverse directions, so temperature is a factor that affects percentage yield.

Since catalysts increase the rate of both the forward and reverse reactions to the same degree, they do not affect the percentage yield of equilibrium reaction products.

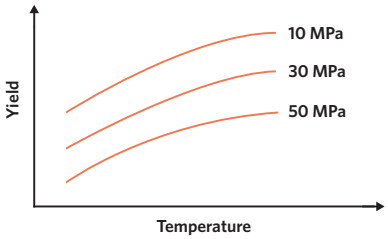
According to Le Chatelier's principle, equilibrium systems will respond to changes in pressure by shifting in either the forward or reverse directions, so pressure is a factor that affects percentage yield.

Therefore, **option C** is correct.

PROGRESS QUESTIONS

Question 1

Gases X, Y, and Z form an equilibrium in a sealed container. The graph below shows the effects of temperature and pressure on the yield of compound Y.



Which of the following equations is consistent with the graph?

A. $X(g) + 3Z(g) \rightleftharpoons 2Y(g)$ $\quad \Delta H > 0$

B. $X(g) + Z(g) \rightleftharpoons 2Y(g)$ $\quad \Delta H < 0$

C. $2X(g) \rightleftharpoons 2Y(g) + Z(g)$ $\quad \Delta H > 0$

D. $2X(g) \rightleftharpoons 2Y(g) + Z(g)$ $\quad \Delta H < 0$

Continues →

Question 2

Which of the following is key to minimising the conflict between rate and yield in an equilibrium reaction?

A. Using toxic solvents

B. Using high temperatures

C. Using catalysts

D. Generating waste products

Question 3

Which of the following is a disadvantage of using high temperatures to promote chemical reactions?

A. Increased yield

B. Increased reaction rate

C. Increased energy efficiency

D. Increased risk of unwanted side reactions

Green chemistry principles – part 2 & designing for energy efficiency 3.2.9.1 & 3.2.9.3

Industrial processes can be designed to use energy in the most efficient way with the fewest carbon emissions.

How 'green' is the ammonia produced from the Haber-Bosch process?

Currently, ammonia produced from the Haber-Bosch process is responsible for approximately half of the global fertiliser production. The nitrogen gas used is sourced from the air we breathe, and is abundant and relatively easy to isolate. The concern of many chemists, however, is the source of hydrogen gas: the steam methane reforming (SMR) process, which is responsible for 90% of the carbon dioxide emissions from the Haber-Bosch process. Hydrogen produced from SMR is known as **grey hydrogen**.

Fortunately, there are a number of promising options for the **decarbonisation** of ammonia production, such as the electrolysis of water to produce green hydrogen (figure 5).[2]

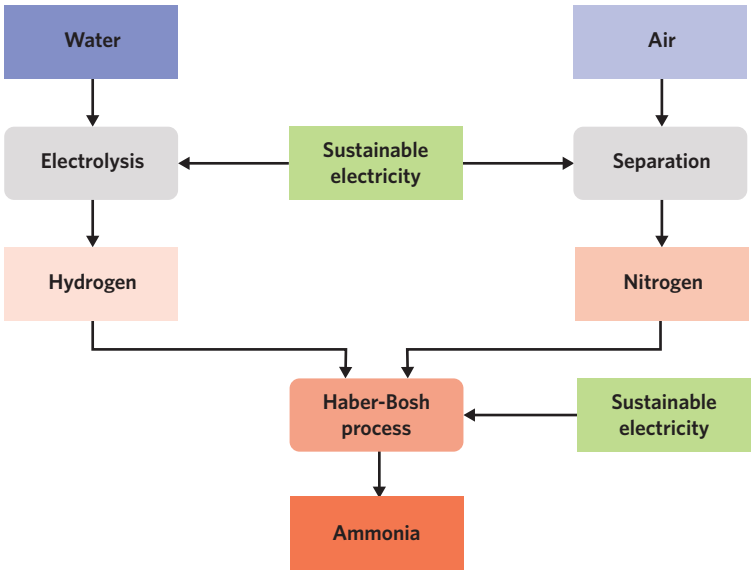


Figure 5 Sustainable production of green ammonia

USEFUL TIP

In lesson 6D, we will learn about the production of green hydrogen in more detail through the process of electrolysis.

KEEN TO INVESTIGATE?

[2] **How many different 'colours' of hydrogen are there?**
Search: The hydrogen colour spectrum

Comparisons of the sources of hydrogen to be used in ammonia production are outlined in table 1.

Table 1 Sources of hydrogen gas for ammonia production

Method	SMR Process – Grey Hydrogen	Electrolysis of water – Green Hydrogen
Reaction(s)	$CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g)$ $CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$	$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$
CO_2 emissions	Responsible for 1.8% of global CO_2 emissions	Net zero emission of CO_2
Energy requirements	Powered by fossil fuels	Powered by renewable energy

MISCONCEPTION

'Net zero carbon emissions means no carbon is emitted at all.'

When a process is described as having net zero carbon emissions, it means that the overall process results in no net production of carbon dioxide from sourcing or consumption.

USEFUL TIP

The UN's Sustainable Development Goals relevant to this study design can be found in the VCE Data Book.

The wide–spread adoption of green hydrogen production to enable the mass production of green ammonia is integral in achieving goal 2 of the United Nations' Sustainable Development Goals: zero hunger. Since ammonia is the key ingredient in fertilisers, the agricultural industry relies heavily on the production of ammonia. Fertilisers produced from green ammonia serve as a sustainable solution for feeding a growing population on a global scale, all while using significantly fewer non-renewable resources and contributing far less to the greenhouse effect.

How can we design equilibrium systems to be more energy efficient?

In lesson 3G, we explored the innovations in energy efficient chemical processes through galvanic cells; specifically, we discussed how fuel cells can be designed to produce sufficient energy to meet society's needs. Designing for energy efficiency is also a key consideration in optimising the formation of equilibrium reaction products, however, the focus is more so on energy consumption than energy production.

Two techniques that are presently being implemented into a number of equilibrium processes include:

- The use of catalysts to increase the rate of reactions in industrial processes, instead of high reaction temperatures.
  - Dramatically reduces energy input, serving both an economic and environmental purpose; lower temperatures are less expensive and require less fuel to maintain.
- The use of heat exchangers to recover wasted heat from exothermic reactions carried out on a large scale.
  - Transfers heat from one place to another, so heat energy given off by a reaction can be recovered and reused to continue powering the reaction, thereby reducing energy input requirements.

PROGRESS QUESTIONS

Question 4

The industrial synthesis of methanol from syngas (a mixture of carbon monoxide and hydrogen gas) is described by the following equation.

$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \qquad \Delta H < 0$

Which of the following could be implemented to improve the energy efficiency of methanol synthesis?

A. Using a zinc oxide catalyst

B. Increasing the temperature

C. Increasing the concentration of reactants

D. Decreasing the pressure

Continues →

Question 5

Which of the following is an example of designing for energy efficiency in an equilibrium reaction?

A. Increasing the temperature of the reaction to increase the reaction rate

B. Using a heat exchanger to recover waste heat from the reaction

C. Using a non-renewable energy source to power the reaction

D. None of the above

Question 6

The carbon footprint of industrial processes can be reduced by

A. using fossil fuels to power the process.

B. using chemicals sourced from processes powered by fossil fuels.

C. using renewable energy sources such as solar panels.

D. using high temperatures and pressures.

Theory summary

- Le Chatelier's principle is used to find the combination of temperature and pressure that optimises the yield of industrial equilibrium reaction products.
- Compromise conditions are reaction conditions that provide the best balance of yield and rate.
  - Despite lowering the overall yield of a desired chemical, many industrial processes will use high temperatures as the rate at which this lower yield is produced is more economically viable.
- Catalysts are used to increase the rate of reactions in industrial processes, especially those carried out at low temperatures.
- Catalysts only affect the rate, they do not affect the yield of the reaction.
- A catalysed reaction produces the same amount of product as an uncatalysed reaction but it produces the product at a faster rate (in a shorter period of time).
- Catalysts are a sustainable option for increasing the rate of reactions as they can often be recycled.
- Using higher temperatures to promote the formation of equilibrium reaction products can cause unwanted side reactions to occur.
- Green hydrogen obtained from the electrolysis of water is a more sustainable source of hydrogen gas than grey hydrogen obtained from steam methane reforming.
- Heat exchangers can be used to reuse waste heat in order to improve the energy efficiency of industrial processes.

5D Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

The industrial production of sulfuric acid can be described as a four-stage process. The first two stages are the burning of raw sulfur with oxygen, followed by the oxidation of sulfur from the +4 to the +6 state.

Question 7 (1 MARK)

What is the equation for the complete combustion of sulfur in oxygen?

A. $S(s) + O(g) \rightleftharpoons SO(g)$

B. $S(s) + O_2(g) \rightleftharpoons SO_2(g)$

C. $S(s) + O(g) \rightarrow SO(g)$

D. $S(s) + O_2(g) \rightarrow SO_2(g)$

Adapted from VCAA 2004 Exam 1 Short answer Q5a

Question 8 (1 MARK)

What is the balanced equation for the oxidation of sulfur from the +4 to the +6 state?

A. $SO_2(g) + O_2(g) \rightleftharpoons SO_3(g)$

B. $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$

C. $SO_3(g) + O_2(g) \rightleftharpoons SO_2(g)$

D. $2SO_3(g) + O_2(g) \rightleftharpoons 2SO_2(g)$

Adapted from VCAA 2004 Exam 1 Short answer Q5bi

Question 9 (3 MARKS)

The oxidation of sulfur from the +4 to the +6 state is an exothermic process.

a. What happens if the temperature in the second stage of this process is too high? 2 MARKS

b. What happens if the temperature in the second stage of this process is too low? 1 MARK

Adapted from VCAA 2004 Exam 1 Short answer Q5bii, iii

Exam-style

Question 10 (2 MARKS)

The following equation represents an equilibrium reaction occurring in a sealed container.

$A(g) + B(g) \rightleftharpoons 5C(g) \qquad \Delta H = +212 \text{ kJ}$

Consider the following sets of conditions used for this equilibrium reaction.

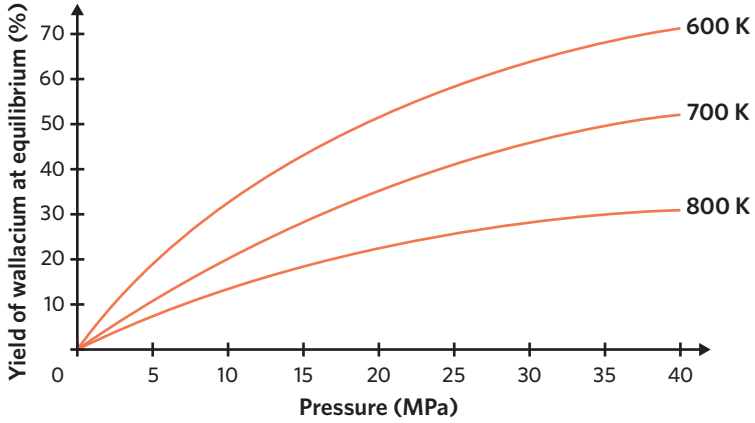
	Temperature (°C)	Pressure (kPa)
I.	50	100
II.	50	200
III.	300	100
IV.	300	200

a. Under which conditions would the highest yield of A(g) be obtained? 1 MARK

b. Under which conditions would the rate of reaction be the highest? 1 MARK

Question 11 (9 MARKS)

Two different factories are competing to run the most efficient wallacium (a fictional chemical) synthesis plant. The following graph shows the equilibrium yield of wallacium at different temperatures and pressures.



Both factories add 6000 kg of reactants to evacuated reaction vessels at the beginning of each day. Factory 1 produces 3000 kg of wallacium per day and operates for 24 hours each day. Factory 2 produces 150 kg of wallacium per hour and operates for 12 hours each day.

a. According to the graph, which combination of temperature and pressure obtains the highest yield of wallacium? 1 MARK

b. Both factories operate at a pressure of 40 MPa and should theoretically convert 100% of the reactants into products. Identify the reaction temperature used in each factory. 3 MARKS

c. Evaluate the efficiency of each wallacium synthesis plant. In your answer, you should refer to the economic benefits of the conditions used by each factory. 5 MARKS

Key science skills

Question 12 (13 MARKS)

The activation energy of the ammonia synthesis reaction given below can be altered through the use of catalysts.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92$ kJ

The following table gives the activation energy for the reaction when several different catalyst mixtures containing combinations of caesium, iron, cobalt, barium and phthalocyanine (Pc) are used.

Catalyst	E_a (kJ mol^{-1})
2% Cs–FePc	52.5
8% Ba–CoPc	60.9
2% Cs–FeCoPc	52.0
10% Cs–FePc	41.9
Fe–benchmark	70

a. According to the data provided, which of the catalysts is most energy efficient in the synthesis of ammonia? 1 MARK

b. What would be the most suitable combination of pressure, temperature and catalyst to optimise the yield of ammonia? 1 MARK

c. In practice, the Haber process is carried out at around 450 °C. Explain why the Haber process is conducted at this relatively high temperature. 2 MARKS

d. What is the purpose of the Fe–benchmark catalyst in this data set? 1 MARK

e. The nitrogen gas used in the synthesis of ammonia is readily available in the air we breathe. The hydrogen gas is primarily sourced from the steam methane reforming process, which is represented by the following equations.

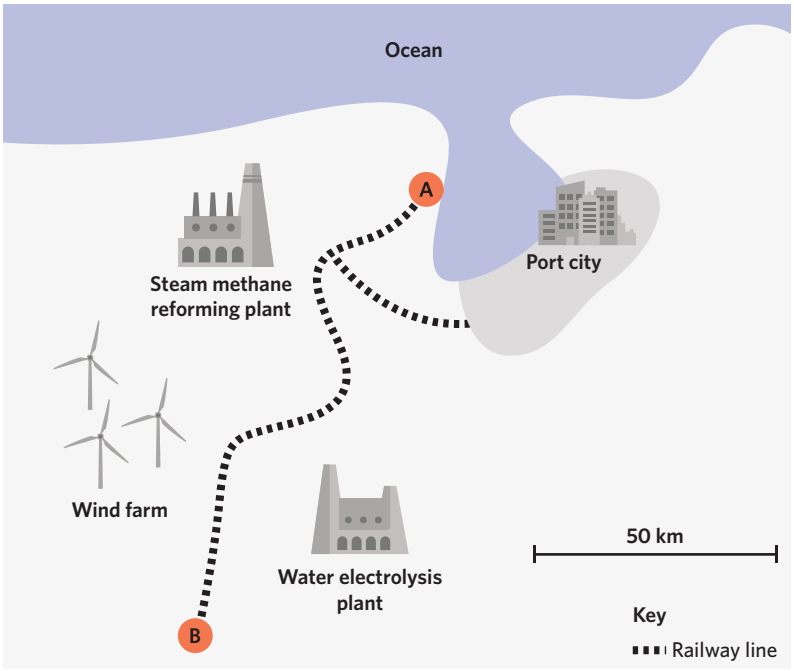
(1) $CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g)$

(2) $CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$

Identify and explain the key environmental concern associated with the steam methane reforming process.

2 MARKS

f. The electrolysis of water is a promising option for the sustainable sourcing of hydrogen for the mass production of ammonia, the key ingredient in the manufacture of fertilisers. The following diagram represents a region where the construction of a new fertiliser plant is being considered.



Given the ammonia will be synthesised at the plant, which of sites **A** or **B** would be the preferred location for the fertiliser plant? Explain your answer by evaluating the logistical and environmental benefits of each site.

6 MARKS

FROM LESSONS 12A, 12B, 12C & 12E

Questions from multiple lessons

Question 13 🌶🌶🌶

(6 MARKS)

Since the early 20th century, scientists have been monitoring the levels of carbon dioxide both in the atmosphere and in the oceans. When carbon dioxide dissolves in water, it forms carbonic acid, $H_2CO_3(aq)$, which dissociates into the hydrogen carbonate ion, $HCO_3^-(aq)$, and a hydrogen ion, and eventually into a carbonate ion, $CO_3^{2-}(aq)$ and a hydrogen ion.

Over the last 50 years, scientists have recorded increases in the following:

- The amount of fossil fuels burnt.
- Atmospheric carbon dioxide levels.
- Average global air temperature.
- Average global ocean temperature.
- The volume of carbon dioxide dissolved in the oceans.

Use the equilibrium formed between carbon dioxide in the air and carbon dioxide in the oceans to explain the scientists' observations. Include any relevant equations in your answer. Limit your discussion to a maximum of 200 words. Dot points are acceptable.

FROM LESSONS 1A, 1D & 5C

Chapter 5 review

Mild Medium Spicy

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which of the following is **not** a characteristic of a dynamic equilibrium system?

A. Equilibrium can only be achieved in a closed system.

B. The equilibrium constant depends on pressure.

C. Equilibrium can be reached from either direction.

D. Equilibrium concentrations of reactants and products are constant.

Question 2 (1 MARK)

Consider the following statements about a reaction system at equilibrium.

I. The concentrations of the reactants and products are always equal.

II. The reaction system contains only reactants.

III. The rate of the forward reaction is equal to the rate of the reverse reaction.

Which of the following correctly identifies the correct statement(s)?

A. I only **B.** III only **C.** I and II only **D.** I and III only

Question 3 (1 MARK)

Hydrogen is produced on an industrial scale from methane. The equation for the reaction is

$2H_2O(g) + CH_4(g) \rightleftharpoons CO_2(g) + 4H_2(g)$

The expression for the equilibrium constant for the reverse reaction is

A. $K = \frac{[H_2O]^2[CH_4]}{[H_2]^4[CO_2]}$ **B.** $K = \frac{[H_2]^4[CO_2]}{[H_2O]^2[CH_4]}$ **C.** $K = \frac{[H_2O][CH_4]}{[H_2][CO_2]}$ **D.** $K = \frac{4[H_2][CO_2]}{2[H_2O][CH_4]}$

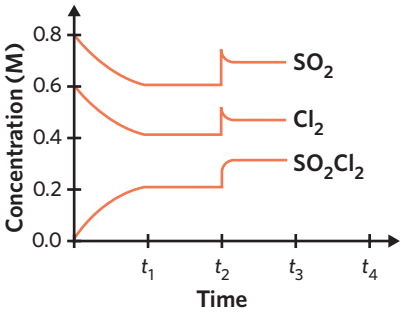
VCAA 2014 exam Multiple choice Q1

Use the following information to answer questions 4–5.

The following equation represents the reaction between sulfur dioxide gas, SO_2, and chlorine gas, Cl_2.

$SO_2(g) + Cl_2(g) \rightleftharpoons SO_2Cl_2(g) \quad \Delta H = -67 \text{ kJ mol}^{-1}$

The following graph shows concentration versus time for the reaction system.



Question 4 (1 MARK)

Which one of the following fully describes the change that took place at time t_2?

A. $SO_2(g)$ and $Cl_2(g)$ were added to the system.

B. A catalyst was added to the system.

C. Argon gas was added to the system.

D. The volume of the system was decreased.

VCAA (NHT) 2022 exam Multiple choice Q14

Question 5 (1 MARK)

At time t_3 the system was in equilibrium. After time t_3 the temperature in the container was decreased and at time t_4 a new equilibrium was established. Which of the following resulted at time t_4?

	At time t_4 the rate of the	At time t_4 the concentration of $SO_2Cl_2(g)$ was
A.	reverse reaction decreased compared to time t_3.	greater than at time t_3.
B.	forward reaction decreased compared to time t_3.	less than at time t_3.
C.	reverse reaction remained the same as at time t_3.	greater than at time t_3.
D.	forward reaction remained the same as at time t_3.	less than at time t_3.

VCAA (NHT) 2022 exam Multiple choice Q15

Question 6 (1 MARK)

An equilibrium is formed between iodide ions and iodine solution to produce the triiodide ion.

$I^-(aq) + I_2(aq) \rightleftharpoons I_3^-(aq)$

0.60 mol of I_3^- is added to an evacuated 2.00 L flask. When the system reaches equilibrium, the flask contains 0.42 mol of I_3^-. What are the concentrations of I^- and I_2 in the flask at equilibrium?

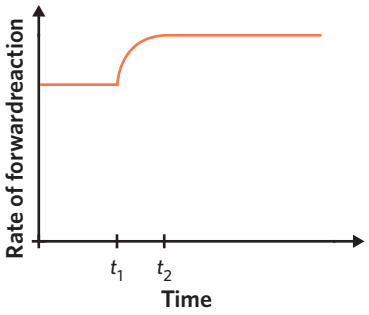
	$[I^-]$ (M)	$[I_2]$ (M)
A.	0.09	0.09
B.	0.09	0.18
C.	0.18	0.18
D.	0.18	0.36

Question 7 (1 MARK)

Hydrogen iodide, hydrogen gas, and iodine gas form an equilibrium mixture represented by the following equation.

$$\underset{\text{Colourless}}{2HI(g)} \rightleftharpoons H_2(g) + \underset{\text{Purple}}{I_2(g)} \quad \Delta H < 0$$

A change was made at time t_1 to an equilibrium mixture of HI, H_2, and I_2, which achieved a new equilibrium at time t_2. A graph showing the rate of the forward reaction is shown below.



Which one of the following describes the change that was made to the initial equilibrium system and the colour change that occurred between t_1 and t_2?

A. The temperature was increased and the colour lightened.

B. The temperature was increased and the colour darkened.

C. The temperature was decreased and the colour lightened.

D. The temperature was decreased and the colour darkened.

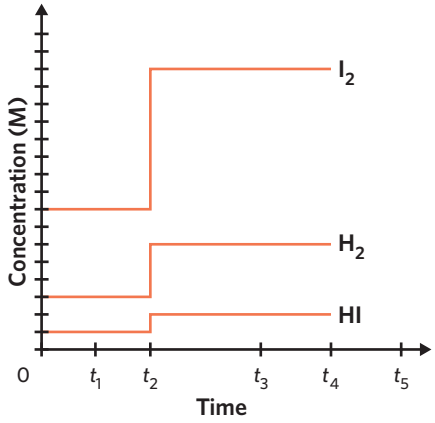
Adapted from VCAA 2020 exam Multiple choice Q19

Use the following information to answer questions 8–9.

Hydrogen, H_2, and iodine, I_2, react to form hydrogen iodide, HI.

$\frac{1}{2}H_2(g) + \frac{1}{2}I_2(g) \rightleftharpoons HI(g) \quad \Delta H = +25.9$ kJ

The graph below shows the concentrations of H_2, I_2 and H_2 in a sealed container. One change was made to the equilibrium system at time t_2.



Question 8 (1 MARK)

Which one of the following statements is correct?

A. A catalyst was added at time t_2.

B. The amount of HI is greater at time t_3 compared with time t_1.

C. The rate of reaction producing HI is the same at time t_1 and time t_3.

D. The rate of production of HI at time t_3 is double the rate of production of H_2 at time t_3.

VCAA 2021 exam Multiple choice Q27

Question 9 (1 MARK)

One change was made to the equilibrium system at time t_4, which altered the equilibrium constant. Equilibrium was re-established at time t_5. The rate of the reverse reaction at time t_5 was higher than at time t_3. Which of the following options correctly shows the change in the equilibrium system from time t_3 to time t_5?

	Change from time t_3 to time t_5	
	Equilibrium constant	**Total chemical energy**
A.	increase	increase
B.	increase	decrease
C.	decrease	increase
D.	decrease	decrease

VCAA 2021 exam Multiple choice Q28

Question 10 (1 MARK)

The following equation represents the equilibrium formed between NO, O_2, and NO_2.

$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$

4.0 mol of NO_2 is added to a sealed 3.0 L reaction vessel and allowed to react. At equilibrium, there is 2.5 mol of NO_2 present in the reaction vessel. What is the equilibrium constant for this reaction?

A. $1.1\ M^{-1}$ **B.** $3.3\ M^{-1}$ **C.** $5.5\ M^{-1}$ **D.** $11\ M^{-1}$

Short answer (30 MARKS)

Question 11 (7 MARKS)

A change in the position of equilibrium can be demonstrated visually using two forms of cobalt(II) ions. Solutions of the $[Co(H_2O)_6]^{2+}$ ion are pink, and solutions of the $CoCl_4^{2-}$ ion are blue. A solution made from 0.5 M $[Co(H_2O)_6]^{2+}$ ions and 5 M Cl^- ions reaches the following equilibrium.

$$\underset{\text{Pink}}{[Co(H_2O)_6]^{2+}(aq)} + \underset{\text{Colourless}}{4Cl^-(aq)} \rightleftharpoons \underset{\text{Blue}}{CoCl_4^{2-}(aq)} + 6H_2O(l)$$

At SLC the mixture is blue when this solution is at equilibrium.

a. Write the equilibrium expression, *K*, for the equation above. 1 MARK

b. A 20 mL sample of the solution above at equilibrium at SLC is placed in a conical flask. The sample is diluted by adding 10 mL of deionised water, H_2O, at SLC. The solution immediately becomes a paler blue due to the dilution. Use Le Chatelier's principle to explain the colour change expected from this paler blue colour until a new equilibrium is reached. 2 MARKS

c. Samples of the original equilibrium solution are pink when refrigerated at 4 °C and blue when kept at 25 °C. Is the forward reaction in the original equilibrium solution endothermic or exothermic? Explain your reasoning. 2 MARKS

d. At SLC, the equilibrium constant for this solution is 9.0×10^{-10} M^{-4}. At a time *t*, the concentrations of $[Co(H_2O)_6]^{2+}$, Cl^- and $CoCl_4^{2-}$ ions in a reaction vessel at SLC are 2.0 M, 4.2 M and 0.030 M respectively. Is the system in equilibrium at time *t*? Justify your answer with a calculation involving the reaction quotient. 2 MARKS

Adapted from VCAA (NHT) 2019 exam Short answer Q7

Question 12 (8 MARKS)

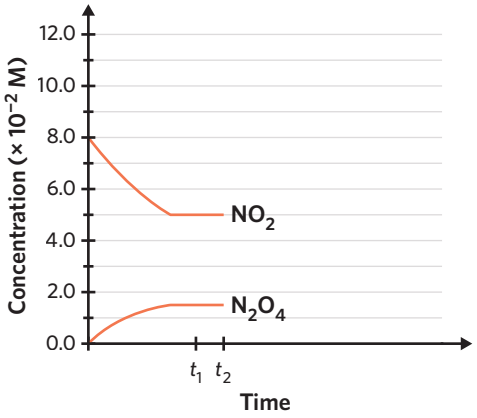
A student is investigating the following reaction system.

$$\underset{\text{Brown}}{2NO_2(g)} \rightleftharpoons \underset{\text{Colourless}}{N_2O_4(g)} \quad \Delta H < 0$$

The reaction system can be observed in a sealed test tube, which allows the student to investigate the impact of temperature on the equilibrium position of the reaction.

a. State the colour change expected when the student places the sealed test tube of the gas mixture in a beaker of hot water. Explain why this colour change occurs. 3 MARKS

b. The concentration versus time graph for the reaction system is shown. The graph was produced using secondary data at a temperature of 22 °C.



i. Time t_1 is shown on the graph. Calculate the equilibrium constant at time t_1. 2 MARKS

ii. At time t_2 the volume of the system was halved, keeping the temperature at 22 °C. Redraw and continue the graph to show how this change would affect the reaction system and how the system would respond to this change until equilibrium is restored. 3 MARKS

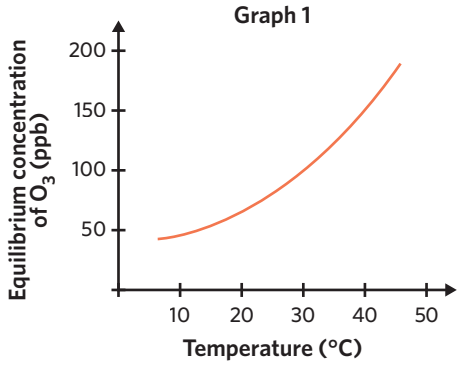
VCAA 2018 exam Short answer Q7

Question 13 (7 MARKS)

In the upper atmosphere, ozone, $O_3(g)$, is formed from oxygen, $O_2(g)$, in the presence of ultraviolet (UV) light. An equation that represents this chemical reaction is given below.

$$3O_2(g) \xrightleftharpoons{\text{UV light}} 2O_3(g)$$

Graph 1 shows the effect of temperature on the equilibrium concentration of $O_3(g)$ in a sealed container containing only $O_2(g)$ and $O_3(g)$. The container is clear and exposed to UV light.



a. With reference to Graph 1, state whether the forward reaction is endothermic or exothermic. Explain your answer. 3 MARKS

b. 7.50×10^{-2} mol of O_2 was placed in an evacuated and sealed 3.00 L container at 30 °C. This clear container was exposed to UV light. At equilibrium, 1.56×10^{-7} mol of O_3 had formed in the container. Calculate the equilibrium constant at 30 °C. 4 MARKS

Adapted from VCAA (NHT) 2022 exam Short answer Q3

Question 14 (8 MARKS)

Nitrosyl chloride, NOCl, is a highly toxic gas used in the chemical industry as an oxidising agent. The formation reaction of NOCl from nitrogen monoxide, NO, and chlorine, Cl_2, is

$$2NO(g) + Cl_2(g) \rightleftharpoons 2NOCl(g) \quad \Delta H > 0$$

This reaction forms an equilibrium above 100 °C. A scientist conducted two experiments on the equilibrium reaction of NOCl. The initial experiments were conducted in evacuated and sealed 4 L containers at 150 °C.

Experiment 1: 2 mol of NOCl was injected into a previously evacuated, sealed 4 L container.
Experiment 2: 4 mol of NOCl was injected into another previously evacuated, sealed 4 L container.

a. Which experiment had the highest initial rate of production of Cl_2? Justify your answer using the factors that affect the rate of a reaction. 2 MARKS

b. If, for Experiment 1, the concentrations of NOCl and NO were equal at equilibrium, [NOCl] = [NO], then what conclusion could be made about the relative concentrations of NOCl and NO in Experiment 2 at equilibrium? Justify your answer. 2 MARKS

c. 2 mol of an inert gas is injected into the container in Experiment 1. The temperature is kept at 150 °C. What effect will this have on the rate of production of the Cl_2 in the container? Justify your answer using the factors that affect the rate of a reaction. 2 MARKS

d. The temperature for Experiment 2 is increased to 200 °C. Explain the effect on the equilibrium concentration of NOCl in the reaction. 2 MARKS

VCAA (NHT) 2018 exam Short answer Q3

Key science skills (10 MARKS)

Question 15 (4 MARKS)

The following equation represents a reaction that takes place in solution.

$FeSCN^{2+}(aq) \rightleftharpoons Fe^{3+}(aq) + SCN^{-}(aq)$
Red colour Pale yellow Colourless

a. Write the equilibrium expression for this reaction. 1 MARK

b. State the units for this equilibrium expression. 1 MARK

c. Complete the table by indicating the effect of each change on the intensity of the red colour of the solution once the new equilibrium has been established. 2 MARKS

		Colour at new equilibrium compared with initial equilibrium	
	Statement	**Less red**	**More red**
I.	Sample 1: 1 drop of a concentrated solution of $Ag^{+}(aq)$ is added, which forms a AgSCN precipitate	☐	☐
II.	Sample 2: 1 drop of a concentrated solution of $Fe^{3+}(aq)$ is added	☐	☐
III.	Sample 3: 1 drop of a concentrated solution of $HPO_4^{2-}(aq)$ is added, which forms colourless $FeHPO_4^{+}(aq)$	☐	☐
IV.	Sample 4: Addition of a large volume of water	☐	☐

Adapted from 2006 VCAA Exam 1 Short answer Q6a

FROM LESSONS 12A & 12C

Question 16 (6 MARKS)

Chemical manufacturers always aim for a high yield where possible, however, this is often balanced by financial, environmental and safety considerations. Discuss the compromises made in chemical industries under the following headings. In your answers, you should identify the compromises made and explain them by linking them to the particular heading.

a. Financial considerations 2 MARKS

b. Energy and environmental considerations 2 MARKS

c. Health and safety considerations 2 MARKS

FROM LESSONS 12B & 12E

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6

CHAPTER 6

Production of chemicals using electrolysis

LESSONS

6A Electrolytic reactions

6B Electrolytic cells

6C Secondary cells

6D Designing cells to produce green hydrogen

6E Faraday's Laws in electrolytic cells

Chapter 6 review

KEY KNOWLEDGE

- the use and limitations of the electrochemical series to explain or predict the products of the electrolysis of particular chemicals, given their state (molten liquid or in aqueous solution) and the electrode materials used, including the writing of balanced equations (with states) for the reactions occurring at the anode and cathode and the overall redox reaction for the cell
- the common design features and general operating principles of commercial electrolytic cells (including, where practicable, the removal of products as they form), and the selection of suitable electrode materials, the electrolyte (including its state) and any chemical additives that result in a desired electrolysis product (details of specific cells not required)
- the common design features and general operating principles of rechargeable (secondary) cells, with reference to discharging as a galvanic cell and recharging as an electrolytic cell, including the conditions required for the cell reactions to be reversed and the electrode polarities in each mode (details of specific cells not required)
- the role of innovation in designing cells to meet society's energy needs in terms of producing 'green' hydrogen (including equations in acidic conditions) using the following methods:
  - polymer electrolyte membrane electrolysis powered by either photovoltaic (solar) or wind energy
  - artificial photosynthesis using a water oxidation and proton reduction catalyst system
- the application of Faraday's Laws and stoichiometry to determine the quantity of electrolytic reactant and product, and the current or time required to either use a particular quantity of reactant or produce a particular quantity of product

Image: GVLR/Shutterstock.com

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6A Electrolytic reactions

STUDY DESIGN DOT POINT

- the use and limitations of the electrochemical series to explain or predict the products of the electrolysis of particular chemicals, given their state (molten liquid or in aqueous solution) and the electrode materials used, including the writing of balanced equations (with states) for the reactions occurring at the anode and cathode and the overall redox reaction for the cell

6A 6B 6C 6D 6E

3.2.10.1 & 3.2.10.2 Balancing electrolytic half-equations & balancing overall electrolytic equations

3.2.10.3 Using the electrochemical series to predict electrolytic reactions

ESSENTIAL PRIOR KNOWLEDGE

3A Redox reactions
3B Writing redox equations
3C Primary galvanic cells
See questions 45–47.



Image: Vadim Sadovski/Shutterstock.com

How do astronauts breathe in space?

Breathable air is created on the International Space Station using an **electrolytic reaction** that produces oxygen from water. In this lesson, we will learn how to balance and predict half-equations and overall equations for electrolytic reactions.

KEY TERMS AND DEFINITIONS

Anode electrode where oxidation (loss of electrons) occurs

Aqueous electrolyte dissolved ionic compound with ions that are free to move (in aqueous state)

Cathode electrode where reduction (gain of electrons) occurs

Electrolytic half-equation one of two equations (oxidation or reduction) that describes one half of an electrolytic reaction

Electrolytic reaction non-spontaneous redox reaction that requires a specified voltage from an external power source to occur

Molten electrolyte melted ionic compound with ions that are free to move (in liquid state)

Balancing electrolytic half-equations & balancing overall electrolytic equations 3.2.10.1 & 3.2.10.2

Electrolytic reactions are a type of non-spontaneous redox reaction whose half-equations must be correctly balanced to accurately represent these reactions. As with spontaneous reactions, KOHES is a helpful mnemonic we can also use to balance **electrolytic half-equations**.

What are electrolytic reactions?

Whilst spontaneous redox reactions allow chemical energy to be converted into electrical energy, electrolytic reactions allow electrical energy to be converted into chemical energy. When a redox reaction is not feasible, the activation energy of this reaction is too high for the reaction to occur.

To combat this, electrolytic reactions require an input of (electrical) energy through a connection to an external power source, which allows non-spontaneous redox reactions to occur.[1]

As explained in lesson 3C, spontaneous redox reactions require the strongest oxidising agent (top left of the electrochemical series) present to be positioned above the strongest reducing agent (bottom right of the electrochemical series) present in order for a reaction to be feasible. An electrolytic reaction, on the other hand, is only feasible if the voltage of the external power source meets a particular threshold. This is applied using either inert or reactive electrodes.

KEEN TO INVESTIGATE?

[1] **How do astronauts breathe in space?**
Search: Breathing easy on the space station

PROGRESS QUESTIONS

Question 1

Electrolytic reactions convert

A. chemical energy into electrical energy.

B. electrical energy into chemical energy.

C. thermal energy into electrical energy.

D. kinetic energy into chemical energy.

Question 2

Can electrolytic reactions occur spontaneously?

A. No, because heat is required.

B. Yes, but they are very slow and so are not observable.

C. No, because an external power source with sufficient voltage is required.

D. Yes, if the strongest oxidising agent present is above the strongest reducing agent present on the electrochemical series.

How can we balance electrolytic half-equations and overall equations?

As electrolytic reactions are a type of redox reaction, electrolytic half-equations can also be balanced using KOHES and combined to form the overall reaction using the same method as for spontaneous redox reactions, explained in lesson 3B. KOHES is summarised again in this lesson for reference.

USEFUL TIP

An electrolytic reaction can be thought of as the reverse reaction of a feasible spontaneous redox reaction.

Key elements need to be balanced.

Oxygen atoms need to be balanced by adding H_2O.

Hydrogen atoms need to be balanced by adding H^+ in acidic environments. (In basic environments, OH^- ions must be added to both sides of the equation to neutralise all H^+ ions.)

Electrons need to be added to balance charge.

States need to be included.

WORKED EXAMPLE 1

Balance the following electrolytic reaction under acidic conditions.

$Cr^{3+}(aq) + NO_3^-(aq) \rightarrow Cr_2O_7^{2-}(aq) + HNO_2(aq)$

What information is presented in the question?

The unbalanced chemical equation for the electrolytic reaction under acidic conditions.

What is the question asking us to do?

Write out the balanced overall equation.

Continues →

What strategies do we need in order to answer the question?

1. Use oxidation states to identify the conjugate redox pairs, which will be reactants and products in each half-equation.
2. Balance each half-equation using KOHES.
3. Make each half-equation have the same number of transferred electrons by multiplying one or both of the equations by a whole number.
4. Add the equations together to determine the overall redox equation.

Answer

The oxidation state of Cr increases from +3 in Cr^{3+} to +6 in $Cr_2O_7^{2-}$, so $Cr_2O_7^{2-}$ and Cr^{3+} form one conjugate redox pair ($Cr^{3+}/Cr_2O_7^{2-}$).

The oxidation state of N decreases from +5 in NO_3^- to +3 in HNO_2, so HNO_2 and NO_3^- form the other conjugate redox pair (NO_3^-/HNO_2).

Using KOHES under acidic conditions, the following unbalanced half-equation can be balanced.

$Cr^{3+} \rightarrow Cr_2O_7^{2-}$

Balance the key element (Cr).

$2Cr^{3+} \rightarrow Cr_2O_7^{2-}$

Balance oxygen by adding H_2O to the side with less oxygen.

$2Cr^{3+} + 7H_2O \rightarrow Cr_2O_7^{2-}$

Balance hydrogen by adding H^+ ions to the side with less hydrogen.

$2Cr^{3+} + 7H_2O \rightarrow Cr_2O_7^{2-} + 14H^+$

Add electrons (e^-) to the side with the most positive charge.

$2Cr^{3+} + 7H_2O \rightarrow Cr_2O_7^{2-} + 14H^+ + 6e^-$

Add states of all species (except electrons).

$2Cr^{3+}(aq) + 7H_2O(l) \rightarrow Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^-$

Again using KOHES under acidic conditions,

$NO_3^- \rightarrow HNO_2$

Is balanced to

$NO_3^-(aq) + 3H^+(aq) + 2e^- \rightarrow HNO_2(aq) + H_2O(l)$

To be able to add these together to form the overall equation, the second equation must be multiplied by three so that each equation contains six electrons.

$3 \times (NO_3^-(aq) + 3H^+(aq) + 2e^- \rightarrow HNO_2(aq) + H_2O(l))$

$3NO_3^-(aq) + 9H^+(aq) + 6e^- \rightarrow 3HNO_2(aq) + 3H_2O(l)$

These half-equations can now be added together to form an overall equation.

$2Cr^{3+}(aq) + 7H_2O(l) + 3NO_3^-(aq) + 9H^+(aq) + 6e^- \rightarrow Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- + 3HNO_2(aq) + 3H_2O(l)$

After cancelling species that appear on both sides of the equation, we are left with the following final balanced overall redox equation where the charge on each side of the equation is +3.

$2Cr^{3+}(aq) + 3NO_3^-(aq) + 4H_2O(l) \rightarrow Cr_2O_7^{2-}(aq) + 5H^+(aq) + 3HNO_2(aq)$

PROGRESS QUESTIONS

Question 3

A particular electrolytic reaction is characterised by the oxidation and reduction half-equations provided.

Reduction: $Na^+(l) + e^- \rightarrow Na(l)$

Oxidation: $Sn(l) \rightarrow Sn^{2+}(l) + 2e^-$

Which of the following represents the balanced overall electrolytic reaction?

A. $Na^+(l) + Sn(l) \rightarrow Na(l) + Sn^{2+}(l)$

B. $2Na^+(l) + Sn(l) \rightarrow 2Na(l) + Sn^{2+}(l)$

C. $Na^+(l) + Sn(l) \rightarrow Na(l) + e^- + Sn^{2+}(l)$

D. $Na^+(l) + 2Sn(l) \rightarrow Na(l) + 2Sn^{2+}(l)$

Question 4

In an electrolytic reaction, the polyatomic sulfate ion, SO_4^{2-}, is reduced to form hydrogen sulfite, HSO_3^-, in an acidic aqueous solution.

What is the balanced reduction half-equation for this reaction?

A. $SO_4^{2-}(aq) + 4H^+(aq) + e^- \rightarrow HSO_3^-(aq) + 2H_2O(l)$

B. $HSO_3^-(aq) + H_2O(l) \rightarrow SO_4^{2-}(aq) + 3H^+(aq) + 2e^-$

C. $SO_4^{2-}(aq) + 3H^+(aq) + 2e^- \rightarrow HSO_3^-(aq) + H_2O(l)$

D. $HSO_3^-(aq) + H_2O(l) \rightarrow SO_4^{2-}(aq) + 2H^+(aq) + e^-$

Using the electrochemical series to predict electrolytic reactions 3.2.10.3

Similar to the process of predicting feasible spontaneous redox reactions under standard conditions, the electrochemical series can be used to determine whether an electrolytic reaction can feasibly occur, and if so, which chemical species are involved in the reaction.

How can the electrochemical series be used to predict electrolytic reactions?

During spontaneous redox reactions, the strongest oxidising agent present (top left) always reacts with the strongest reducing agent present (bottom right). This is the same during electrolytic reactions (figure 1). Like in primary galvanic cells, oxidation occurs at the **anode** and reduction occurs at the **cathode** during electrolysis. This will be explained further in lesson 6B.

Note that as with predicting feasible spontaneous redox reactions, the electrochemical series can only be reliably used to predict feasible electrolytic reactions under standard conditions (25 °C or 298 K, 100 kPa).

USEFUL TIP

Unlike in spontaneous redox reactions, in electrolytic reactions, the strongest oxidising agent (highest on the left) will be positioned below the strongest reducing agent present (lowest on the right) (figure 1).

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \leftarrow Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$	−0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	−0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	−0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	−0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	−0.44
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	−0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	−0.83

Figure 1 Predicted electrolytic reaction of 1.0 M $Sn^{2+}(aq)$ and 1.0 M $Pb^{2+}(aq)$ using silver electrodes (assuming voltage threshold has been met)

As in spontaneous redox reactions, it is important to consider water as a potential reactant when aqueous reactants are present. For example, if a solution containing 1.0 M Na^+ and 1.0 M Cl^- were electrolysed using inert electrodes under standard conditions, only water could feasibly initially undergo oxidation and reduction. This is because water is both the strongest reducing and oxidising agent present (figure 2).

MISCONCEPTION

'Reactive metals like Na, Al, K, and Ca can be extracted from solutions.'

When electrolysed under standard conditions, water will undergo reduction in preference to dissolved ions of some reactive metals if water is a stronger oxidising agent than the metal ions. In this case, the metal ions would remain in the solution.

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	−0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	−0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	−1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	−2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	−2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	−2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	−2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	−3.04

Figure 2 Predicted electrolytic reaction of 1.0 M NaCl(aq) (assuming voltage threshold has been met)

In industry, **molten electrolytes** are often used rather than **aqueous electrolytes** to overcome this. Molten electrolytes are created by the melting of an ionic compound such as NaCl(s) at very high temperatures, in this case approximately 800 °C. Therefore, liquid sodium and chloride ions, $Na^+(l)$ and $Cl^-(l)$, are formed. Note that an electrolytic reaction involving these reactants would typically occur at non-standard temperatures. However, in VCAA exams, the electrochemical series can still be used for these reactions.

USEFUL TIP

A concentrated NaCl solution is also known as a 'brine'.[2]

Sometimes non-standard concentrations are also used to obtain a product in a reaction that is not feasible under standard conditions. The electrochemical series also cannot be used to reliably predict reactions in these conditions. These concepts were covered in lessons 3C (limitations of the electrochemical series) and 5C (optimising yield of chemical reactions). For example, when 5.0 M NaCl(aq) is electrolysed using inert electrodes, chlorine gas is produced even though this is not predicted by the electrochemical series. However, $Cl^-(aq)$ will not indefinitely undergo oxidation; this will be covered in lesson 6B.

KEEN TO INVESTIGATE?

[2] **How are brines used to preserve food?**
Search: Brining, curing, pickling common salt

PROGRESS QUESTIONS

Question 5

Which of the following is/are true?

When writing balanced electrolytic reactions, the electrochemical series can

I. identify the strongest oxidising agent and reducing agent present.

II. identify the overall reaction that occurs when the voltage and concentrations are unknown.

III. identify only the oxidation half-equation.

A. I and II only

B. I only

C. II and III only

D. I and III only

Theory summary

- Electrolytic half-equations can be balanced using the mnemonic KOHES.
- A complete electrolytic reaction can be determined by adding the reduction and oxidation half-equations together if they contain the same number of electrons, or one or both half-equations are multiplied by a whole number so that both half-equations contain the same number of electrons.
- The electrochemical series can help us identify the strongest oxidising agent present (top left) and the strongest reducing agent present (bottom right).
- An electrolytic reaction generally occurs between the strongest oxidising agent and the strongest reducing agent present.
- The electrochemical series is only reliable to predict redox reactions under standard laboratory conditions (25 °C or 298 K, 100 kPa) and 1.0 M concentrations.

6A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 6–8.

A power supply is connected to inert electrodes partially submerged in a 1.0 M K_2SO_4 solution under standard conditions. The following standard half-reaction and its standard electrode potential is provided in addition to those in the VCE Data Book.

$S_2O_8^{2-}(aq) + 2e^- \rightleftharpoons 2SO_4^{2-}(aq) \quad E^0 = +2.01\ V$

Question 6 (1 MARK)

What is the strongest oxidising agent present?

A. $H_2O(l)$
B. $SO_4^{2-}(aq)$
C. $S_2O_8^{2-}(aq)$
D. $K^+(aq)$

Question 7 (1 MARK)

What is the strongest reducing agent present?

A. $SO_4^{2-}(aq)$
B. $H_2O(l)$
C. $S_2O_8^{2-}(aq)$
D. $K^+(aq)$

Question 8 (1 MARK)

Which one of the following equations represents the overall redox reaction reaction that occurs?

A. $2H_2O(l) \rightarrow O_2(g) + 2H_2(g)$
B. $O_2(g) + 2H_2(g) \rightarrow 2H_2O(l)$
C. $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$
D. $2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

Adapted from VCAA 2010 Exam 2 Multiple choice Q18

Exam-style

Question 9 (1 MARK)

If the following is a spontaneous redox reaction, what electrolytic reaction would be predicted given a sufficient voltage?

$3Se(s) + 4Cr(OH)_3(aq) + 6OH^-(aq) \rightarrow 3SeO_3^{2-}(aq) + 4Cr(s) + 9H_2O(l)$

A. $3SeO_3^{2-}(aq) + 4Cr(s) \rightarrow 3Se(s) + 4Cr(OH)_3(aq)$

B. $3Se(s) + 4Cr(OH)_3(aq) \rightarrow 3SeO_3^{2-}(aq) + 4Cr(s)$

C. $3SeO_3^{2-}(aq) + 4Cr(s) + 9H_2O(l) \rightarrow 3Se(s) + 4Cr(OH)_3(aq) + 6OH^-(aq)$

D. $Se(s) + Cr(OH)_3(aq) + OH^-(aq) \rightarrow SeO_3^{2-}(aq) + Cr(s) + H_2O(l)$

Question 10 (1 MARK)

Why is it not possible to extract magnesium metal, Mg(s), by electrolysing a 1.0 M MgI_2 solution?

A. Water is a stronger reducing agent than I^-.

B. Water is a stronger oxidising agent than I^-.

C. Water is a stronger reducing agent than Mg^{2+}.

D. Water is a stronger oxidising agent than Mg^{2+}.

Adapted from VCAA 2010 Exam 2 Multiple choice Q20

Question 11 (4 MARKS)

Zoran would like an electrolytic reaction to occur between $Ni^{2+}(aq)$ and Pb(s). They use lead electrodes dipped into aqueous 1.0 M $Ni^{2+}(aq)$ and a power source. Zoran states that it does not matter what voltage is applied for an electrolytic reaction to occur, and all that matters is the presence of a power source. However, when they use a power source with a small voltage, nothing happens.

a. Evaluate Zoran's statement with reference to their observations. 2 MARKS

b. Write the oxidation and reduction half-equations for the feasible reactions. 2 MARKS

Question 12 (3 MARKS)

The unbalanced chemical equation provided represents an electrolytic reaction that occurs in a rechargeable lead-acid car battery.

$Pb^{2+}(aq) + H_2O(l) \rightarrow Pb(s) + PbO_2(s) + H^+(aq)$

a. Write the balanced oxidation half-equation for the reaction in acidic conditions. 1 MARK

b. Write the balanced reduction half-equation for this reaction in acidic conditions. 1 MARK

c. Write the full balanced redox equation for this reaction. 1 MARK

Question 13 (3 MARKS)

The unbalanced electrolytic equation between molten iron and molten magnesium sulfate is given, assuming a sufficient voltage is provided.

$Fe(l) + Mg^{2+}(l) \rightarrow Fe^{3+}(l) + Mg(l)$

a. Write the balanced oxidation and reduction half-equations for this electrolytic reaction. 2 MARKS

b. Write the balanced overall electrolytic equation for this reaction. 1 MARK

Question 14 (2 MARKS)

1.00 M $Cu^{2+}(aq)$ and $Co^{2+}(aq)$ are dissolved, and using platinum electrodes, a sufficient voltage is applied. A student predicts that $Co^{2+}(aq)$ will be reduced in favour of $Cu^{2+}(aq)$ under standard conditions. With reference to the electrochemical series, is the student's prediction correct?

Key science skills

Question 15 🌶🌶 (8 MARKS)

A chemist aims to electrolyse a 1.0 M NaCl(aq) solution under standard conditions. The power source is connected and switched on for 10 minutes at a sufficient voltage and gases formed at each electrode are collected.

a. Identify the gases formed at each electrode. Justify your answer with relevant oxidation and reduction half-equations. 4 MARKS

b. For hydrogen gas, H_2, identify

i. a risk associated with this gas. 1 MARK

ii. a precaution to minimise this risk. 1 MARK

c. When molten NaCl is electrolysed, the only gas produced is chlorine gas, Cl. Identify

i. a risk associated with this gas. 1 MARK

ii. a precaution to minimise this risk. 1 MARK

FROM LESSON 12B

Questions from multiple lessons

Question 16 🌶🌶 (5 MARKS)

The following reaction is an example of a spontaneous redox reaction.

$Ni(s) + 2Ag^+(aq) \rightarrow Ni^{2+}(aq) + 2Ag(s)$

a. Write the two half-equations for this redox reaction. 2 MARKS

b. Determine the conjugate redox pair for

i. the oxidation process. 1 MARK

ii. the reduction process. 1 MARK

c. Given sufficient voltage and using silver electrodes, what will be the overall electrolytic equation when a solution of 1.0 M $Ni^{2+}(aq)$ is electrolysed using silver electrodes? 1 MARK

FROM LESSONS 3A & 3B

Question 17 🌶🌶 (3 MARKS)

Mia was in a chemistry class studying redox reactions. She initially had a beaker with a blue solution of 1.0 M $Cu^{2+}(aq)$ ions and accidentally put a strip of Pb(s) in the beaker. The following redox reaction occurred.

$Cu^{2+}(aq) + Pb(s) \rightarrow Cu(s) + Pb^{2+}(aq)$

a. Is this an electrolytic reaction? Explain your answer. 2 MARKS

b. Write out the reaction that would occur if, using copper electrodes, a solution of Pb^{2+} ions were electrolysed. 1 MARK

FROM LESSONS 3B & 3C

6B Electrolytic cells

STUDY DESIGN DOT POINT

- the common design features and general operating principles of commercial electrolytic cells (including, where practicable, the removal of products as they form), and the selection of suitable electrode materials, the electrolyte (including its state) and any chemical additives that result in a desired electrolysis product (no specific cell is required)

6A 6B 6C 6D 6E

3.2.11.1 Design of electrolytic cells

3.2.11.2 Selecting electrolytes, electrodes, and additives

ESSENTIAL PRIOR KNOWLEDGE

3C Anode and cathode
3D Cell voltage
6A Electrolytic reactions

See questions 48–50.



Image: VladKK/Shutterstock.com

How is gold-plated jewellery made?

Many industries use **electroplating** to apply a layer of one metal (e.g. gold) on top of another metal. This is done to improve its appearance and/or prevent corrosion. In this lesson, we will learn how **electrolytic cells** can facilitate reactions like electroplating reactions.

KEY TERMS AND DEFINITIONS

Additive a substance added to improve or optimise a chemical process
Electrolytic cell cell that facilitates electrolytic (non-spontaneous redox) reactions
Electroplating application of a layer of a metal onto another metal during an electrolytic reaction
Polarity (in electrochemical cells) overall charge of an electrode
Standard electrode potential (E^0) potential of a half-cell reaction, given in volts (V), relative to the Standard Hydrogen Electrode

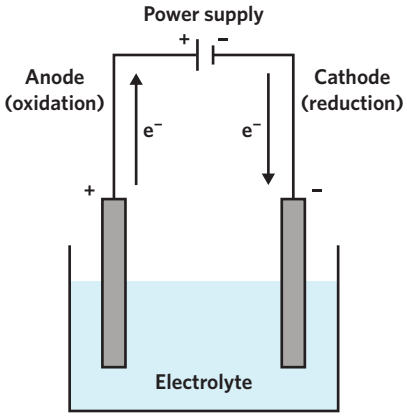


Figure 1 Design of an electrolytic cell

USEFUL TIP

Figure 1 uses two vertical lines to represent a battery/power supply. The longer of the two lines represents the positive terminal, and the shorter represents the negative terminal.

Design of electrolytic cells 3.2.11.1

Electrolysis allows non-spontaneous reactions to occur when electrical energy is applied to the system using a power source. The design and function of electrolytic cells, which facilitate these reactions, will be explored in this lesson.

How are electrolytic cells designed to transform electrical energy into chemical energy?

As explored in lesson 6A, electrolytic reactions require a voltage input from an external power source in order to occur. Whilst galvanic cells convert chemical energy into electrical energy through spontaneous redox reactions (lesson 3C), electrolytic cells facilitate non-spontaneous redox reactions, converting electrical energy into chemical energy.

Electrolytic reactions are initiated by connecting a power supply to the circuit, providing the necessary electrical energy to reach the reaction's activation energy. Electrical energy from the power supply provides the flow of electrons needed to force a non-spontaneous reaction to occur. The general design of an electrolytic cell is given in figure 1.

By definition, oxidation occurs at the anode of this cell, and reduction occurs at the cathode. However, the **polarities** of these electrodes differ from those in a primary galvanic cell (table 1). In an electrolytic cell, the cathode is the negative (−) electrode (figure 2) and the anode is the positive (+) electrode (figure 3). Despite these differences in polarities, electrons flow from the anode to the cathode through the external circuit (wire) in both primary galvanic cells and electrolytic cells.

USEFUL TIP

Electrons always flow away from the site of oxidation (anode) towards the site of reduction (cathode) in the circuit.

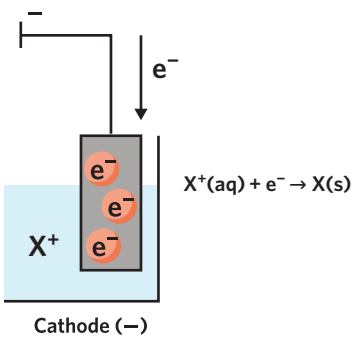


Figure 2 The power source sends electrons towards the cathode, where they are involved in the reduction half-reaction.

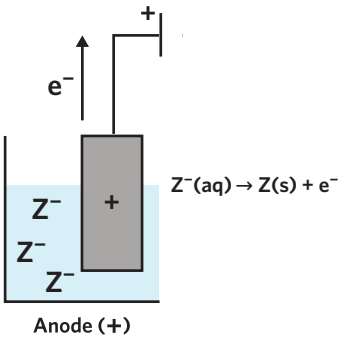


Figure 3 Electrons released during the oxidation half-reaction are drawn towards the positively charged terminal of the power supply.

Table 1 Polarities in different cells

	Primary galvanic cells		Electrolytic cells	
Electrode	Anode	Cathode	Anode	Cathode
Polarity	Negative (−)	Positive (+)	Positive (+)	Negative (−)
Reason	Electrons (negative charge) released at the anode during oxidation make the electrode negative.	Electrons (negative charge) that flow towards the cathode are involved in the reduction half-reaction.	Electrons (negative charge) are forced away from the cathode by the power supply. The anode is the electrode connected to the positive terminal of the power supply.	Electrons (negative charge) are sent towards the cathode by the power supply. The cathode is the electrode connected to the negative terminal of the power supply.

As electrolytic reactions are non-spontaneous under standard conditions, the reactants will not directly react, and so the anode and cathode in an electrolytic cell, as well as the electrolyte, may be contained in the same vessel. However, any products formed must be kept separate, as they are likely to spontaneously react undesirably (and sometimes dangerously). Often, this involves either the removal of a product as it forms, or the inclusion of a screen (mesh) separating the electrodes, as shown in figure 4.

USEFUL TIP

The products of electrolytic reactions will be reactants of a spontaneous redox reaction. Therefore, they can feasibly react if not separated.

Similar to the electrolyte in primary galvanic cells, the electrolyte in electrolytic cells allows ions (charge) to flow, completing the internal circuit, while electrons flow through a wire from the anode to the cathode in the external circuit. This is shown in figure 4, in the Downs Cell. Note that specific electrolytic cells are not required knowledge in VCE chemistry.

USEFUL TIP

When a single gaseous product is formed during electrolysis, it escapes the cell before it is considered able to react with other products produced.

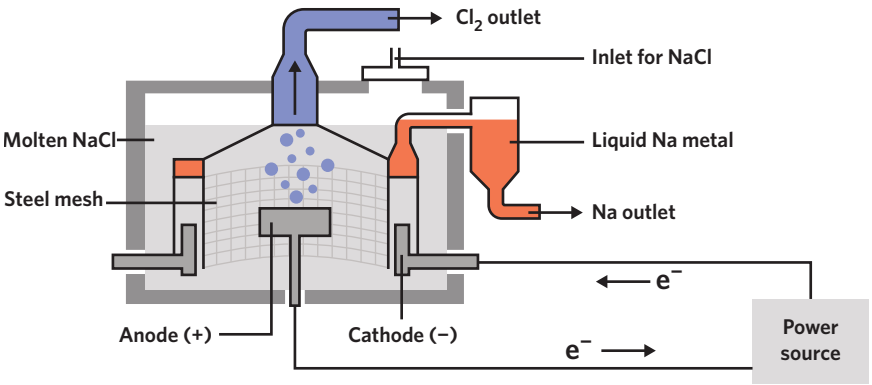


Figure 4 Design of Downs Cell

USEFUL TIP

Comparisons of the design and function of electrolytic cells and primary galvanic cells are no longer required in the VCE Study Design. However, practising questions requiring these skills may still be helpful.

PROGRESS QUESTIONS

Question 1

Electrolytic cells all have a

A. positively charged anode as the site of reduction.

B. negatively charged anode as the site of oxidation.

C. positively charged anode as the site of oxidation.

D. negatively charged anode as the site of reduction.

Question 2

An electrolytic cell is set up with two platinum electrodes in a solution of tin(II) chloride using a sufficient voltage. The reaction occurring at the positive electrode under standard conditions would be

A. $Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$

B. $Sn^{2+}(aq) \rightarrow Sn^{4+}(aq) + 2e^-$

C. $2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

D. $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$

How can we determine the voltage required to operate an electrolytic cell?

STRATEGY

When calculating voltages from standard electrode potentials, always subtract the least positive E^0 value from the most positive E^0 value. In galvanic cells the most positive is reduced, whereas in electrolytic cells the most positive is oxidised.

MISCONCEPTION

'An electrolytic reaction will occur if the predicted minimum voltage from the electrochemical series is applied.'

A greater voltage than the minimum predicted voltage from the electrochemical series is required to facilitate an electrolytic reaction under standard conditions due to energy loss in the cell.

An important application of the electrochemical series is that it can be used to predict the required voltage required from an external power source to facilitate an electrolytic reaction in an electrolytic cell.

As explained in lesson 3D, the right column of the electrochemical series in the VCE Data Book lists the **standard electrode potentials (E^0)** that correspond to each of the half-reactions given. Similar to calculating the cell voltage of a primary galvanic cell, these values can be used to calculate the voltage input required to facilitate the reaction. This is found by subtracting the E^0 value for the reduction half-reaction from the E^0 value for the oxidation half-reaction, as shown.

$$E_{\text{required}} > E^0_{\text{most positive value (oxidation)}} - E^0_{\text{least positive value (reduction)}}$$

A 'greater than' sign (>) is used to indicate that a larger voltage than this threshold is required for a particular electrolytic cell to function. This greater voltage input is required due to energy loss in the cell, typically as heat (resistance in wires).

USEFUL TIP

In exams, responses giving the voltage required for an electrolytic cell to operate must always be given with a 'greater than' sign. For example, ' >+1.23V '.

WORKED EXAMPLE 1

An electrolytic cell with graphite (carbon) electrodes contains 1.0 M aqueous lead(II) ions and bromide ions. What is the voltage required to allow the reaction to proceed?

What information is presented in the question?

This is an electrolytic reaction.

Lead(II) ions are present in an aqueous state.

Bromide ions are present in an aqueous state.

Water is present.

What is the question asking us to do?

Calculate the voltage required for this reaction to proceed under standard conditions.

Continues →

What strategies do we need in order to answer the question?

1. Outline the species present on the electrochemical series.
2. The strongest oxidising agent (top left) always reacts with the strongest reducing agent (bottom right).
3. Apply the formula $E_{required} > E^0_{most\ positive\ value\ (oxidation)} - E^0_{least\ positive\ value\ (reduction)}$
4. Include a 'greater than' (>) sign in the final answer.

Answer

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \leftarrow 2Br^-(aq)$	+1.09
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$	−0.13
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	−0.83

The strongest oxidising agent present (top left: Pb^{2+}) will react with the strongest reducing agent present (bottom right: Br^-) according to the following equations.

Reduction: $Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$ $\quad E^0 = -0.13$ V

Oxidation: $2Br^-(aq) \rightarrow Br_2(l) + 2e^-$ $\quad E^0 = +1.09$ V

To calculate the required voltage:

$E_{required} > E^0_{oxidation} - E^0_{reduction}$

$E_{required} > +1.09\ V - (-0.13\ V)$

$E_{required} > +1.22$ V

Therefore, a voltage of >+1.22 V is required for this cell to operate.

PROGRESS QUESTIONS

Question 3

What voltage is required for an electrolytic cell with inert electrodes and a $CuCl_2(aq)$ electrolyte to operate under standard conditions?

A. +0.89 V **B.** −1.02 V **C.** >+0.89 V **D.** <−1.02 V

How do competitive electrolytic reactions change over time?

When there are two or more oxidising or reducing agents present, the reaction occurring may be replaced by a different reaction over time as concentrations of reactants and products change. This means that as the concentration of the strongest oxidising/reducing agent decreases, the half-reaction involving the next strongest oxidising/reducing agent will be favoured. This can be explained by principles of equilibrium (lesson 5C), but is not required knowledge in VCE chemistry.

This property of redox reactions is especially useful when extracting metals from impure ores or solutions containing multiple metal ions. Note that as mentioned in lesson 6A, metal cations that are weaker oxidising agents than water cannot be extracted from a solution under standard conditions; the reduction half-reaction involving water is favoured.

MISCONCEPTION

'If an ion is initially present, its corresponding atom must also be present.'

Ions (e.g. Cu^{2+}) may be present without their corresponding atom (e.g. Cu) for a redox reaction to occur.

USEFUL TIP

You may see the power supply for an electrolytic cell be referred to as a 'DC power supply'. This means that the power supply provides direct current, a current that consistently flows in a single direction, as opposed to alternating current, where the direction of current is constantly changing (inappropriate choice for electrolytic cell).

WORKED EXAMPLE 2

An electrolytic cell is constructed using inert electrodes containing 1.0 M $Pb^{2+}(aq)$, $Co^{2+}(aq)$, and $Ni^{2+}(aq)$. Assuming a sufficient voltage is provided by a DC power supply, in what order are metals from the solution predicted to be plated on the cathode? List your responses from the inside (first plated) to outside (last plated).

What information is presented in the question?

Inert electrodes are used.

1.0 M $Pb^{2+}(aq)$, $Co^{2+}(aq)$, and $Ni^{2+}(aq)$ are initially present in the solution.

Water is present.

A sufficient voltage is provided for these electrolytic reactions to occur.

What is the question asking us to do?

Determine the order (inside (first plated) to outside (last plated)) that these metals are plated.

What strategies do we need in order to answer the question?

1. Outline all species present on the electrochemical series.
2. The strongest oxidising agent present (top left) reacts with the strongest reducing agent present (bottom right).
3. As the concentration of the strongest oxidising/reducing agent decreases, the half-reaction involving the next strongest oxidising/reducing agent will be favoured.

Answer

The species initially present are outlined as shown.

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	−0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	−0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	−0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	−0.28

The strongest oxidising agent present is predicted to be reduced first according to the reaction:

$Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$

Therefore, lead, Pb, is predicted to be plated onto the cathode first.

As the concentration of $Pb^{2+}(aq)$ in the solution decreases, the reduction half-reaction involving the next strongest oxidising agent (top left) available is predicted to be favoured according to the reaction:

$Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

Therefore, nickel, Ni, is predicted to be plated next.

As the concentration of $Ni^{2+}(aq)$ in the solution decreases, the reduction half-reaction involving the next strongest oxidising agent (top left) remaining is predicted to be favoured according to the reaction:

$Co^{2+}(aq) + 2e^- \rightarrow Co(s)$

This means that cobalt is predicted to be plated next.

While each of these reactions occur, oxygen is formed at the anode according to the oxidation half-reaction involving water and the pH is decreasing.

$H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

Therefore, the order the metals are plated onto the cathode (from inside (first plated) to outside (last plated) is: Pb(s), Ni(s), Co(s).

Selecting electrolytes, electrodes, and additives 3.2.11.2

Appropriate electrolytes, electrodes, and **additives** must be selected for an electrolytic cell to operate as desired.

How are electrolytes selected in electrolytic cells?

In industry, an electrolyte in an electrolytic cell must be specifically chosen to minimise expense due to energy requirements, and to ensure that the desired reaction takes place. As mentioned in lesson 6A, there are two main types of electrolyte: molten and aqueous.

As the strongest reducing agent present generally reacts with the strongest oxidising agent present: an aqueous electrolyte can be used in a cell where both

- the desired oxidising agent is a stronger oxidising agent than water (i.e. must be higher on the left of the electrochemical series than water).
- the desired reducing agent is a stronger reducing agent than water (i.e. must be lower down on the right of the electrochemical series than water).

However, if this is not the case, a molten electrolyte can be used instead. In this case, the pure liquid state, (l), is used to indicate molten form, meaning no water is present in the cell when a molten electrolyte is selected. It is preferable to use an aqueous electrolyte where possible, as molten electrolytes require high temperatures to maintain their molten form, and so are both expensive and potentially dangerous to use.

USEFUL TIP

When molten electrolytes are used, the temperature the cell must operate at is often high enough that products predicted to be solid by the electrochemical series (at standard conditions) will melt. Therefore, these can be written with liquid (l) state.

WORKED EXAMPLE 3

The Downs Cell is a particular electrolytic cell that produces sodium metal and chlorine gas using inert electrodes. Use the electrochemical series to predict whether the cell will require a molten or aqueous electrolyte for the desired reaction to occur.

What information is presented in the question?

This reaction occurs in an electrolytic cell.

Sodium metal is produced.

Chlorine gas is produced.

What is the question asking us to do?

Deduce whether the electrolyte for this cell should be aqueous or molten.

What strategies do we need in order to answer the question?

1. Identify the half-equations in the electrochemical series that correspond to this reaction.
2. Outline all species present on the electrochemical series.
3. The strongest oxidising agent present (top left) generally reacts with the strongest reducing agent present (bottom right).

Answer

If the reactants are in aqueous form,water, $H_2O(l)$ is present in the cell. $Na^+(aq)$ and $Cl^-(aq)$ are present.

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \leftarrow 2H_2O(l)$	+1.23
$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$	−0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	−1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	−2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	−2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	−2.87

As water is a stronger oxidising agent than Na^+ and a stronger reducing agent than Cl^-, water is predicted to be reduced and oxidised in preference to Na^+ and Cl^-, so the following half-reactions are predicted to occur.

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

If a molten electrolyte is selected, only $Na^+(l)$ and $Cl^-(l)$ are present.

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \leftarrow 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	−2.37
$Na^+(aq) + e^- \rightarrow Na(s)$	−2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	−2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	−2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	−3.04

This means that Na^+ is reduced and Cl^- is oxidised according to the following half-equations.

$Na^+(l) + e^- \rightarrow Na(l)$

$2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$

The desired reaction only occurs when a molten electrolyte is selected. Therefore, a molten electrolyte must be used in the Downs Cell.

PROGRESS QUESTIONS

Question 4

An electrolytic cell is set up with inert platinum, Pt, electrodes.

Which of the following will produce a gas at the cathode when undergoing electrolysis in the cell?

A. Potassium iodide, KI(aq)

B. Sodium chloride, NaCl(l)

C. Lead bromide, $PbBr_2$(l)

D. Copper sulfate, $CuSO_4$(aq)

VCAA 2022 exam Multiple choice Q13

How can additives optimise processes in electrolytic cells?

Additives are species that can be added to electrochemical cells to optimise cell processes without interfering with electrolytic cell reactions. In particular, cryolite, Na_3AlF_6, is commonly added to the molten Al_2O_3 electrolyte during the extraction of pure aluminium via electrolysis to lower the melting point of the electrolyte from over 2000 °C without cryolite, to approximately 940 °C with cryolite (figure 5). This means that the cell can operate at lower temperatures, making it cheaper and safer to run.

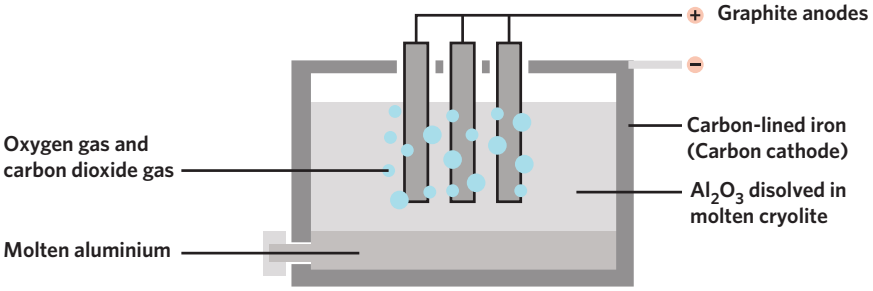


Figure 5 Use of cryolite during the extraction of aluminium through electrolysis

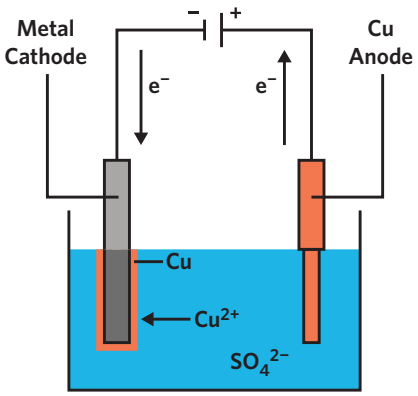


Figure 6 An electroplating cell in which copper is plated onto a strip of metal

How are electrodes selected in electrolytic cells?

As when selecting the electrolyte, selecting electrodes for an electrolytic cell depends on the desired products. When choosing materials for electrodes, it is important to consider whether the electrode is intended to take part in the reaction.

For example, electroplating cells are designed so that metal ions from the electrolyte are deposited on the cathode, and a metal anode is selected such that the concentration of metal ions remains constant (e.g. Cu(s) anode in Cu^{2+}(aq)). Electroplating is most commonly used to either alter the appearance of a metal, or to protect strong reducing agents with a coating of a metal that is less likely to oxidise (figure 6).[1] Otherwise, inert electrodes such as platinum or graphite rods may be used to avoid any undesired reactions occurring.

As in primary galvanic cells, electrodes in electrolytic cells must be solid, conductive, and not cause any undesired reactions in the cell.

KEEN TO INVESTIGATE?

[1] **How does gold plating work?**
Search: How gold plating is done, step by step

MISCONCEPTION

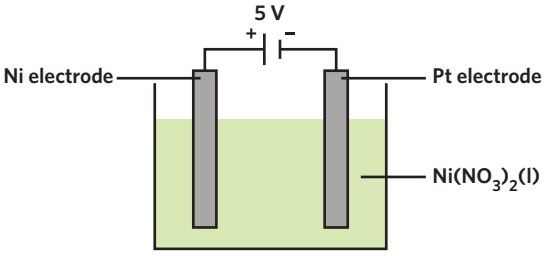
'Graphite (carbon) electrodes will never react.'

Graphite electrodes may react with species in an electrolysis cell. For example, carbon rods used in aluminium production must be periodically replaced as oxygen gas formed during electrolysis reacts with carbon in the electrodes (combusts), producing carbon dioxide gas (figure 5).

PROGRESS QUESTIONS

Question 5

An electrolytic cell with a 5 V power supply is shown.



Using the electrochemical series, which one of the following changes to the electrolytic cell may reduce the amount of Ni electroplated onto the cathode?

A. Replacing the Ni electrode with a Cu electrode

B. Replacing $Ni(NO_3)_2(l)$ with 1 M $Ni(NO_3)_2(aq)$

C. Replacing the Pt electrode with Pb(s)

D. Replacing $Ni(NO_3)_2(l)$ with $NiCl_2(l)$

VCAA 2021 exam Multiple choice Q21

Theory summary

- Electrolytic cells facilitate non-spontaneous redox reactions.
- Electrolytic cells convert electrical energy to chemical energy.
- An electrolytic cell has the following design features:

Feature	Function
Anode	• Electrode where oxidation always occurs • Is positive in an electrolytic cell • Must be an electrically conductive material • Can be either an inert or reactive material
Cathode	• Electrode where reduction always occurs • Is negative in an electrolytic cell • Must be an electrically conductive material • Can be either an inert or reactive material
Electrolyte (aqueous)	• Is used in favour of a molten electrolyte when possible • Ionic salt (aqueous) • Aqueous (aq) state • Water is present so must be considered as a potential reactant • Can easily operate at SLC
Electrolyte (molten)	• Ionic salt (liquid) • Pure liquid (l) state • No water present • Must operate at high temperatures (melting point of ionic salt) • Are expensive and often hazardous (to operate at high temperatures)

Continues →

Feature	Function
Power supply	• Provides the necessary energy for an electrolytic reaction to proceed • Produces a voltage (V) between the anode and cathode • Must be DC (direct current: current that consistently flows in a single direction)
Separation/removal of products	• Products of electrolytic reactions must be separated as they may react spontaneously.
Wire	• Allows flow of electrons from the anode to the cathode in an electrolytic cell • Forms the external circuit

- $E_{\text{required}} > E^0_{\text{most positive value (oxidation)}} - E^0_{\text{least positive value (reduction)}}$
- Cryolite is an additive that can be used to lower the melting point of the electrolyte in the extraction of pure aluminium via electrolysis.

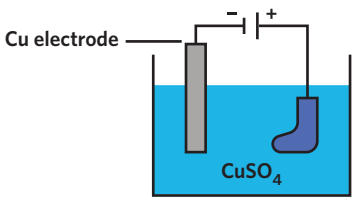
6B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed

Use the following information to answer questions 6–8.

The tradition of bronzing baby shoes dates back for generations. Before electroplating, the shoe is painted with a conductive material. A cell containing a copper, Cu, electrode and copper sulfate, $CuSO_4$, solution used for electroplating a shoe is shown.
Assume this cell operates under standard conditions.



Question 6 🌶 (1 MARK)

During the electroplating process

A. the copper electrode is oxidised and its mass is unchanged.
B. the shoe is coated with copper metal at the cathode.
C. the copper electrode is the oxidising agent.
D. oxygen is produced at the cathode.

VCAA 2019 exam Multiple choice Q17

Question 7 🌶 (1 MARK)

Suppose the $CuSO_4$ solution is replaced with a 1.0 M $Mn(NO_3)_2(aq)$ solution. Which of the following would be the strongest oxidising agent present in this new cell?

A. $H_2O(l)$ **B.** $NO_3^-(aq)$ **C.** $Cu(s)$ **D.** $Mn^{2+}(aq)$

Question 8 🌶🌶 (3 MARKS)

This cell is allowed to run for an extended period of time using a 1.0 M $Mn(NO_3)_2(aq)$ electrolyte.
Is solid manganese, Mn, predicted to be plated onto the shoe using this cell?

Exam-style

Question 9 🌶 (1 MARK)

Which of the following statements regarding electrolytic cells is correct?

A. The species present determine whether oxidation or reduction occurs at the cathode.
B. Electrolytic cells require half-cells to be separated.
C. A redox reaction takes place in the cell.
D. Electrolytic cells convert chemical energy to electrical energy.

Question 10 (1 MARK)

What is the main purpose of the additive cryolite, Na_3AlF_6, in the extraction of pure aluminium from Al_2O_3?

A. Is involved in a secondary reaction, decreasing waste

B. Increases the rate of reaction, reducing production time

C. Reduces the melting point of molten Al_2O_3, reducing operating costs

D. Causes a shift in the equilibrium position, increasing the percentage yield

---

Question 11 (1 MARK)

A molten mixture of equal parts aluminium fluoride, AlF_3, and sodium chloride, NaCl, undergoes electrolysis.

Which of the following statements about this reaction is correct?

A. Sodium metal will be produced at the cathode and fluorine gas will be produced at the anode.

B. Sodium metal will be produced at the anode and chlorine gas will be produced at the cathode.

C. Aluminium metal will be produced at the cathode and chlorine gas will be produced at the anode.

D. Aluminium metal will be produced at the anode and fluorine gas will be produced at the cathode.

VCAA 2019 exam Multiple choice Q7

Question 12 (6 MARKS)

A student prepares a beaker with a solution of tin(II) ions and manganese(II) ions and adds two carbon electrodes connected to a power source. The student predicts that a gas will be produced. However, no bubbling was observed during the reaction.

a. Why did the student's prediction not match the observation? Justify your response with reference to the electrochemical series. 3 MARKS

b. Write the two half-equations for the reactions happening at the anode and cathode. 2 MARKS

c. What effect would using a molten electrolyte have on the overall reaction in the cell? 1 MARK

Question 13 (13 MARKS)

A cell is to be constructed to convert lithium ions to solid lithium from lithium chloride, LiCl, using a carbon anode and a carbon cathode.

a. What type of electrolyte (molten or aqueous) would be more suitable for this cell? Justify your response using evidence from the electrochemical series. 2 MARKS

b. Two cells are constructed and tested with different anodes: one with an iron anode and carbon cathode (cell 1) and the other with a carbon anode and iron cathode (cell 2). It is found that the cells create different products, even with all other factors controlled. Assume the electrolyte determined to be more suitable in part **a** is used.

i. Explain this result, providing the reactions happening at the anode in each case. 4 MARKS

ii. Which of either cell 1 or cell 2 would result in the desired reaction and both electrodes remaining intact? 4 MARKS

c. Another cell is now constructed using a platinum electrode for the anode, the electrolyte identified in your answer to part **a**, and graphite as the cathode. This cell is supplied with 1.05 V and it is observed that no products are created. Explain this result, using calculations in your answer. 3 MARKS

Key science skills

Question 14 (12 MARKS)

A new industrial company is looking for a way to produce solid sodium using electrolysis. The first proposal is presented by the company's chemical engineer, who suggests the use of a platinum cathode, a solid copper anode, and aqueous sodium and nitrate ions as the electrolyte. The requirements of the project are that the cost must be minimised, and the safety of all factory employees be taken into account.

a. Evaluate whether the electrolyte required should be in aqueous or molten form, and propose a way to reduce the cost of running this cell. 4 MARKS

b. The company requests a model for the proposed setup. Draw a diagram of an electrolytic cell that could be used, assuming any change in part a has been implemented, and that the vessels are not required to be separated. Include the polarity of the electrodes, the flow of electrons, the power source, the material of each electrode, the predicted required voltage, and the state of the electrolyte. 6 MARKS

c. The final step in the planning process to consider the second requirement of the project, which is the safety of the employees. The OHS manager of the project finds the Safety Data Sheet for sodium metal and is required to report back to the company. Using the Safety Data Sheet given, identify one risk involved, and a measure to reduce this risk. 2 MARKS

Safety Data Sheet
Product: SODIUM
Formula: Na(s)

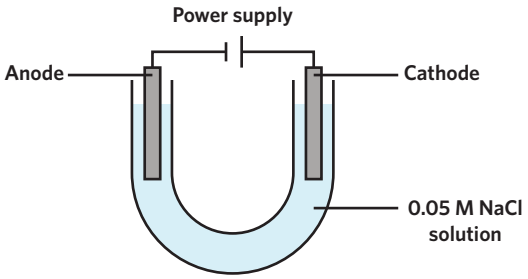
Hazard Statements
In contact with water releases flammable gases which may ignite spontaneously
Causes severe skin burns and eye damage



FROM LESSONS 12B & 12D

Question 15 (6 MARKS)

A student electrolysed a 0.05 M sodium chloride, NaCl, solution using graphite electrodes, as shown in the setup provided.



Several drops of phenol red were added to the solution next to each electrode.

The following observations were made as the reaction proceeded.

Polarity of electrode	Observation	Colour of phenol red
positive	Bubbles formed at the electrode.	yellow
negative	Bubbles formed at the electrode.	red

a. What colour was observed at the cathode as the electrolysis proceeded? 1 MARK

b. Use the electrochemical series to predict the gas expected to be formed at each electrode. 2 MARKS

c. Molten NaCl can be electrolysed commercially. The melting point of NaCl is 801 °C.

i. Write the overall equation for this electrolysis. 1 MARK

ii. Give **two** reasons why it would be difficult to carry out this electrolysis in a school laboratory. 2 MARKS

VCAA (NHT) 2019 exam Short answer Q3

FROM LESSON 12B

Questions from multiple lessons

Question 16 (4 MARKS)

A chemistry student is studying the differences between primary galvanic cells and electrolytic cells. They summarise their findings in a series of statements, but two of their statements are incorrect. Identify the two incorrect statements, and rewrite them to give an accurate statement about electrolytic cells and primary galvanic cells.

Statement 1 'Both galvanic and electrolytic cells require a power supply to operate.'

Statement 2 'A galvanic cell converts chemical energy to electrical energy, and an electrolytic cell converts electrical energy to chemical energy.'

Statement 3 'The anode and cathode of a galvanic cell have the same polarity as the anode and cathode of an electrolytic cell.'

FROM LESSON 3C

Question 17 (10 MARKS)

People who have braces with metal brackets are advised not to bite aluminium foil, as this action can sometimes cause an electric shock as a current flows through conductive tissue.

a. Provide the half-equations for the reaction that causes this electric shock. 2 MARKS

b. Is this an electrolytic reaction? Explain. 2 MARKS

c. Identify the materials of the anode and the cathode in this reaction. 1 MARK

d. Is there an electrolyte present while this reaction occurs? If so, identify the electrolyte and explain its role. 3 MARKS

e. Calculate the maximum voltage predicted to be produced between the electrodes under standard conditions. 1 MARK

f. Why does this reaction not occur when someone without braces bites aluminium foil? 1 MARK

FROM LESSONS 3B, 3C & 6A

6C Secondary cells

STUDY DESIGN DOT POINT

- the common design features and general operating principles of rechargeable (secondary) cells, with reference to discharging as a galvanic cell and recharging as an electrolytic cell, including the conditions required for the cell reactions to be reversed and the electrode polarities in each mode (details of specific cells not required)

6A 6B **6C** 6D 6E

3.2.12.1 Design of secondary cells

3.2.12.2 Recharging secondary cells

ESSENTIAL PRIOR KNOWLEDGE

3B Writing redox equations
3C Primary galvanic cells
6A Electrolytic reactions
6B Electrolytic cells

See questions 51–54.

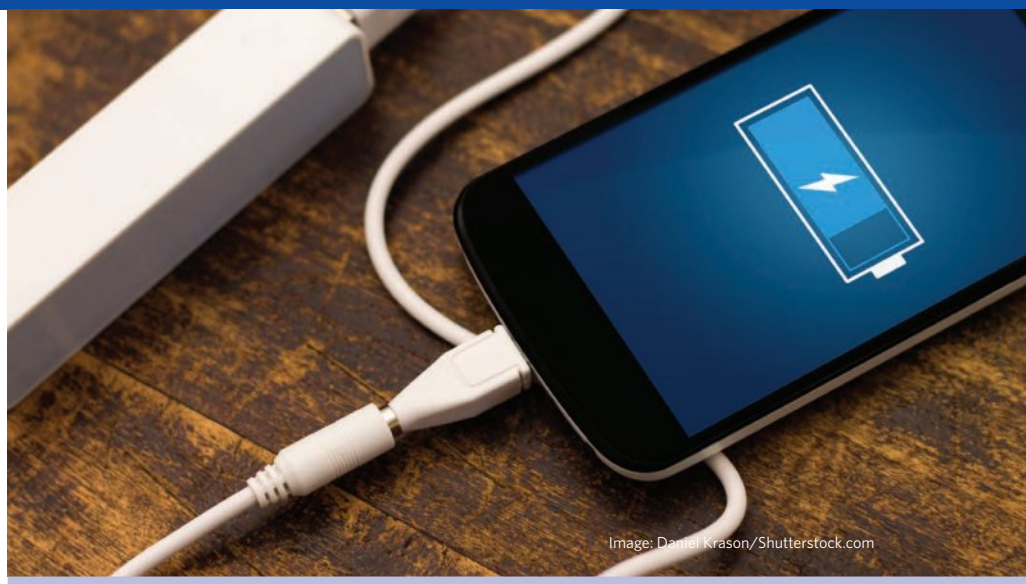


Image: Daniel Krason/Shutterstock.com

What makes phone batteries rechargeable?

Rechargeable **batteries** (also known as **secondary cells**) are electrochemical cells that are commonly used in devices such as mobile phones and cars. In this lesson, we will learn about the design and function of secondary cells.

KEY TERMS AND DEFINITIONS

Battery device consisting of cells that convert chemical energy into electrical energy
Discharge conversion of chemical energy into electrical energy as a result of spontaneous redox reactions
Recharge conversion of electrical energy into chemical energy through electrolytic reactions
Secondary cell electrochemical cell that can be recharged

Design of secondary cells 3.2.12.1

Secondary cells are rechargeable galvanic cells that can be reused many times.

How are secondary cells designed to be rechargeable?

Secondary (rechargeable) cells are increasingly popular galvanic cells that are used in laptops, cameras, and mobile phones. During **discharge** (figure 1), secondary cells function similarly to primary galvanic cells, converting chemical energy (stored within the bonds of the reactants) into electrical energy via spontaneous redox reactions (figure 2). When connected to a power supply, they function similarly to an electrolytic cell, converting electrical energy into chemical energy via electrolytic reactions (non-spontaneous redox reactions) (figure 3). Once **recharged**, the products of these electrolytic reactions are able to spontaneously react (discharge), allowing the battery to be reused.

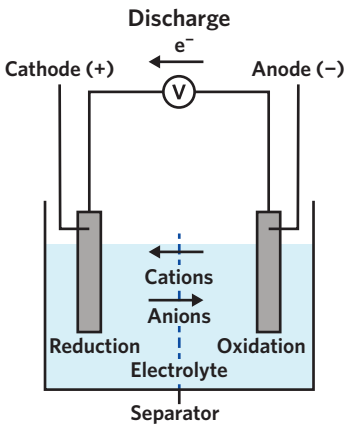


Figure 1 Secondary cell during discharge (spontaneous redox reaction)

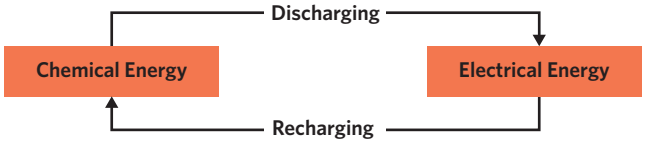


Figure 2 Energy transformations in secondary cells

The key features of secondary cells are outlined in table 1.

Table 1 Design features of secondary cells

Feature	Function	
	Discharge	**Recharge**
Anode (AnOx)	Negative (−) electrode	Positive (+) electrode
Cathode (RedCat)	Positive (+) electrode	Negative (−) electrode
Power supply	N/A	• Provides voltage to initiate electrolytic reaction • Positive terminal is connected to positive electrode; negative electrode is connected to negative electrode
Electrolyte	• Allows flow of ions within the cell (internal circuit) • Cations flow towards the cathode • Anions flow towards the anode	
Separator	• Separates the anode and the cathode • Allows transfer of ions between electrodes	
Wire	• Allows flow of electrons between electrodes (external circuit) • Electrons always flow from the site of oxidation (anode) towards the site of reduction (cathode).	

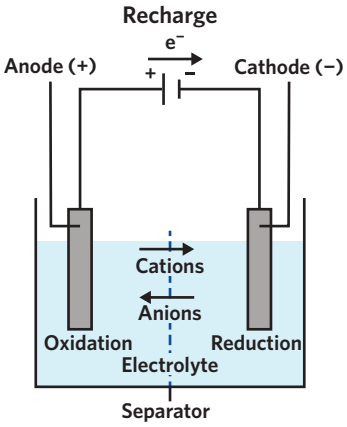


Figure 3 Secondary cell during recharge (non-spontaneous (electrolytic) redox reaction)

USEFUL TIP

The charge of an electrode will remain the same during discharge and recharge.

USEFUL TIP

When recharging a battery, always connect the positive terminal of a power supply to the positive electrode, and the negative terminal to the negative electrode, as shown in figure 3.

MISCONCEPTION

'The polarity of the electrodes is the same in all electrochemical cells.'

During spontaneous redox reactions, the cathode is positive (+) and the anode is negative (−). During non-spontaneous (electrolytic) reactions, the anode is positive (+) and the cathode is negative (−).

PROGRESS QUESTIONS

Question 1

What is the key difference between primary and secondary cells?

A. Primary cells are rechargeable; secondary cells are non-rechargeable.

B. Secondary cells are rechargeable; primary cells are non-rechargeable.

C. Secondary cells are galvanic cells, primary cells are not.

D. Primary cells are galvanic cells, secondary cells are not.

Question 2

A battery

A. can always be recharged.

B. has a positive terminal known as the anode during discharge.

C. converts chemical energy to electrical energy during discharge.

D. has a positive terminal known as the cathode during recharge.

Continues →

Question 3

Most mobile phones have a lithium-ion battery that allows the phone to be recharged many times. Which of the following is/are correct about the process of a phone battery being recharged?

I. Non-spontaneous reaction

II. Spontaneous reaction

III. Acts as a galvanic cell

IV. Acts as an electrolytic cell

A. I only **B.** I and III only **C.** II and III only **D.** I and IV only

Question 4

Rechargeable batteries

A. use reversible reactions.

B. operate as galvanic cells during recharge.

C. operate as electrolytic cells during discharge.

D. require a continuous flow of reactants to operate.

Adapted from VCAA 2021 exam Multiple choice Q1

Recharging secondary cells 3.2.12.2

Secondary cells can only be recharged when certain conditions are met. It is possible to express the reactions that occur in secondary cells through their half-equations and overall equations.

How can we represent recharge and discharge reactions in secondary cells?

As discussed earlier, secondary cells will behave similarly to primary galvanic cells during discharge, and like electrolytic cells during recharge. That is, they will undergo spontaneous redox reactions as the cell discharges, and electrolytic reactions when an appropriate power supply is connected for the cell to be recharged.

You may recall from lesson 6A that an electrolytic (non-spontaneous redox) reaction can be thought of as the reverse reaction of a feasible spontaneous redox reaction. Similarly, the discharge (spontaneous redox) reaction (and its half-reactions) in a secondary cell will be the reverse reaction of the recharge (electrolytic/non-spontaneous redox) reaction (and its half-reactions). Remember from lesson 3A that the reverse reaction of a reduction half-reaction will be an oxidation half-reaction, and vice versa.

WORKED EXAMPLE 1

A widely used secondary cell is the lead-acid battery. The overall discharge reaction for a lead-acid battery is

$Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$

During recharge, what is the reaction at the cathode?

What information is presented in the question?

The overall discharge reaction.

What is the question asking us to do?

Determine the reaction at the cathode during recharge.

Continues →

What strategies do we need in order to answer the question?

1. The recharge reaction in a secondary cell is the reverse reaction of the discharge reaction.
2. The cathode is the site of reduction.
3. Reduction involves a gain of electrons and a decrease in oxidation number.

Balance half-equations using KOHES:

4. Balance key elements.
5. Balance oxygen atoms using H_2O.
6. Balance hydrogen atoms using H^+.
7. In basic conditions, add an OH^- to each side of the equation for every H^+ ion. In basic environments, OH^- ions must be added to both sides of the equation to neutralise all H^+ ions.
8. Balance charge using electrons.
9. Add states.

Answer

The overall recharge reaction of the battery is the reverse reaction of the overall discharge reaction.

$2PbSO_4(s) + 2H_2O(l) \rightarrow Pb(s) + PbO_2(s) + 2H_2SO_4(aq)$

When $PbSO_4(s)$ in the reactants is converted to Pb(s), the oxidation state of Pb decreases from +2 to 0. This means that reduction occurs, and the conjugate redox pair in this reaction is $PbSO_4(s)/Pb(s)$.

An unbalanced reduction half-equation for this reaction is

$PbSO_4 \rightarrow Pb$

Using KOHES, the key elements must be balanced. As there are SO_4^{2-} ions present in the products as $H_2SO_4(aq)$, this can be used to balance sulfur, S.

$PbSO_4 \rightarrow Pb + SO_4^{2-}$

There are 4 oxygen atoms on either side of the half-equation, so no H_2O needs to be added, and there are no H atoms present to be balanced with $H^+(aq)$. Only electrons must be balanced so that each side of the half-equation has a charge of −2.

$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$

Finally, states are added to complete the final balanced reduction half-equation. These are taken from the original overall equation in the question.

$PbSO_4(s) + 2e^- \rightarrow Pb(s) + SO_4^{2-}(aq)$

Adapted from VCAA 2021 exam Multiple choice Q13

PROGRESS QUESTIONS

Question 5

The silver oxide-zinc battery is rechargeable and utilises a sodium hydroxide, NaOH, solution as the electrolyte. This battery is used as a backup in spacecraft for if the primary energy supply fails.

The overall reaction during discharge is

$Zn + Ag_2O \rightarrow ZnO + 2Ag$

When the silver oxide-zinc battery is being **recharged**, the reaction at the anode is

A. $2Ag + 2OH^- \rightarrow Ag_2O + H_2O + 2e^-$

B. $Ag_2O + H_2O + 2e^- \rightarrow 2Ag + 2OH^-$

C. $ZnO + H_2O + 2e^- \rightarrow Zn + 2OH^-$

D. $Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$

VCAA 2018 exam Multiple choice Q16

When can a secondary cell be recharged?

For a secondary cell to be able to be recharged, it must meet the following two conditions:

- The cell must be connected to a power supply that provides a voltage above the required voltage.
- The products of the discharge half-reactions must remain in contact with the electrode at which they react.

Voltage requirements

As mentioned earlier, a secondary cell acts as an electrolytic cell while it is recharged. This means that in order for the recharge reaction in a secondary cell to occur, a particular voltage threshold must be met.

This was discussed in greater detail in lesson 6B. This voltage threshold is calculated as shown under standard conditions. Note that the voltage required to initiate an electrolytic reaction is always expressed with a '>' (greater than) sign. This is to account for energy loss as the cell operates, generally as heat.

$$E_{\text{required}} > E^0_{\text{most positive value (oxidation)}} - E^0_{\text{least positive value (reduction)}}$$

Products of discharge reactions

Once the required voltage threshold has been reached, a recharge reaction can only occur if the products of the discharge half-reactions are in contact with the electrode at which they react. Otherwise, they are unable to be electrolysed. For this reason, it is ideal for a secondary cell to contain predominantly aqueous species, since as long as the electrodes are submerged (figure 4), electrolytic reactions are predicted given a sufficient voltage.[1]

Over time, as a battery undergoes numerous recharge and discharge cycles, a sufficient proportion of products of the discharge reaction may be unable to remain in contact with their relevant electrodes for the cell to operate as desired. This is one of the main factors affecting the longevity of secondary cells, including commercial rechargeable batteries.

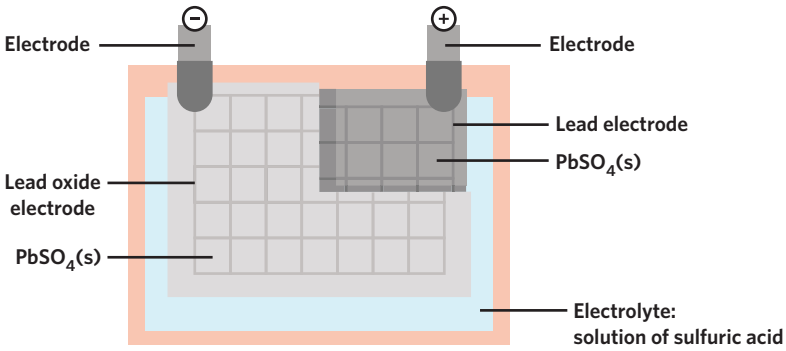


Figure 4 $PbSO_4(s)$ forms at both electrodes during discharge and remains in contact with them until recharge.

KEEN TO INVESTIGATE?

[1] **Are vanadium redox flow batteries the future of energy storage?**
Search: Vanadium redox flow batteries can provide cheap, large-scale grid energy storage

KEEN TO INVESTIGATE?

[2] **Why is it bad to overcharge batteries and how can this be prevented?**
Search: The damage caused by overcharging battery and how to prevent it

USEFUL TIP

High temperatures can cause unwanted side reactions to occur in batteries (once their activation energies are reached), which consume reactants and products of the cell and prevent these from remaining in contact with their electrodes. Overcharging can have a similar effect.[2] At colder temperatures, species in the cell may crystalise (solidify), preventing the flow of ions. Both of these factors affect battery life.

PROGRESS QUESTIONS

Question 6

Consider a secondary cell with Cu^{2+}/Cu and Zn^{2+}/Zn standard half-cells.

What is the required voltage for this cell to be recharged?

A. $+1.10$ V **B.** $>+1.10$ V **C.** >-0.42 V **D.** -0.52 V

Question 7

Which of the following does **not** decrease a secondary cell's ability to be recharged?

A. Formation of aqueous products during discharge reactions

B. Crystallisation

C. Overcharging

D. High operating temperatures

Theory summary

- Secondary cells are rechargeable galvanic cells that are used in devices where it is desirable to reuse the battery, i.e. in phones and laptop computers.
- Electrolytic reactions are used to recharge secondary cells (electrical energy → chemical energy).
- Spontaneous redox reactions occur when a secondary cell discharges (chemical energy → electrical energy).
- The key design features of secondary cells are:
  - Anode (negative during discharge, positive during recharge)
  - Cathode (positive during discharge, negative during recharge)
  - Electrolyte
  - Separator
  - Wire (external)
  - Power supply (recharge only)
- In secondary cells, the discharge reaction is the reverse reaction of the recharge reaction.
- A sufficient voltage is required for a secondary cell to be recharged: $E_{\text{required}} > E^0_{\text{most positive value (oxidation)}} - E^0_{\text{least positive value (reduction)}}$
- For a secondary cell to be recharged, products of the discharge reaction must remain in contact with the electrode at which they react.

6C Questions

Mild Medium Spicy

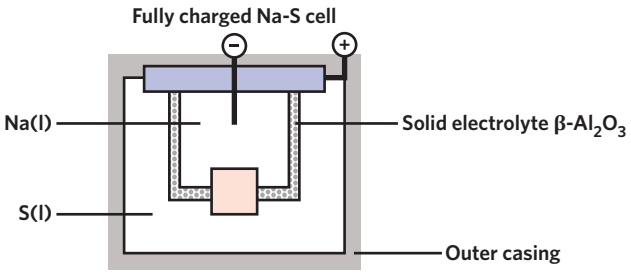
Deconstructed

Use the following information to answer questions 8–10.

Researchers are developing rechargeable cells containing sodium, Na, and sulfur, S.

A simplified diagram of a fully charged Na-S cell is shown below.

The solid electrolyte consists of ceramic beta-alumina, β-Al_2O_3, which is a good conductor of ions. β-Al_2O_3 separates the two half-cells and selectively conducts sodium ions, Na^+.



Question 8 (1 MARK)

Environmental conditions can influence reactions during the discharge of the battery. When a particular Na-S test cell is discharging, the half-equation for the reaction at one of the electrodes is

$3S(l) + 2e^- \rightarrow S_3^{2-}(l)$

Which of the following represents the half-reaction that occurs at the other electrode?

A. $S_3^{2-}(l) \rightarrow 3S(l) + 2e^-$

B. $Na^+(l) + e^- \rightarrow Na(l)$

C. $3S(l) + 2e^- \rightarrow S_3^{2-}(l)$

D. $Na(l) \rightarrow Na^+(l) + e^-$

Adapted from VCAA (NHT) 2022 exam Short answer Q7b

Question 9 (1 MARK)

When the Na-S test cell is discharging, solid sodium trisulfide, Na_2S_3, is formed. What is the overall equation for the recharge process in this cell?

A. $Na_2S_3(s) \rightarrow 2Na(l) + 3S(l)$

B. $2Na(l) + 3S(l) \rightarrow Na_2S_3(s)$

C. $Na_2S_3(s) \rightarrow Na(l) + S(l)$

D. $Na(l) + S(l) \rightarrow Na_2S_3(s)$

Adapted from VCAA (NHT) 2022 exam Short answer Q7b

Question 10 (3 MARKS)

Identify and explain **one** factor that may affect the useful life of the Na-S test cell. You may use chemical equations in your answer.

Adapted from VCAA (NHT) 2022 exam Short answer Q7b

Exam-style

Question 11 (3 MARKS)

The nickel-cadmium rechargeable battery is commonly used in battery-operated devices such as power tools. The half-equations for the half-reactions that occur in this battery during discharge under standard conditions are shown.

$Cd(s) + 2OH^-(aq) \rightarrow Cd(OH)_2(s) + 2e^-$ $\quad E^0 = -0.82$ V

$2NiO(OH)(s) + 2H_2O(l) + 2e^- \rightarrow 2Ni(OH)_2(s) + 2OH^-(aq)$ $\quad E^0 = +0.60$ V

a. What is the maximum voltage produced when the battery discharges? 1 MARK

b. What is the voltage required to recharge this battery? 1 MARK

c. Which half-reaction will occur at the cathode during discharge? 1 MARK

Question 12 (4 MARKS)

Lead-acid batteries are commonly used in cars and other vehicles. They use lead, Pb, and lead oxide, PbO_2, electrodes, and they discharge according to the following half-reactions.

Oxidation (at lead electrode): $Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4(s) + 2e^-$

Reduction (at lead oxide electrode): $PbO_2(s) + SO_4^{2-}(aq) + 4H^+(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l)$

a. Write out the overall reaction during recharge. 2 MARKS

b. Which electrode will be the cathode as the cell recharges? 1 MARK

c. Both discharge reactions produce solid lead oxide, $PbSO_4(s)$. What must occur in order for this battery to be rechargeable? 1 MARK

Question 13 (3 MARKS)

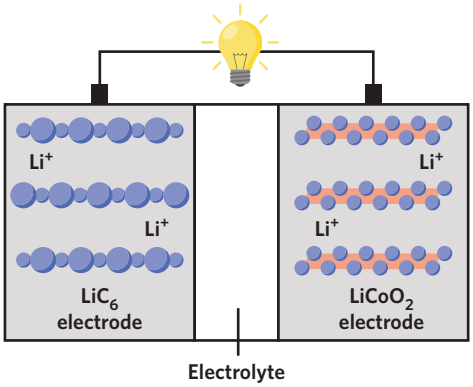
The lithium button cell, used to power watches and calculators, is a primary cell containing lithium metal. The lithium-ion cell is a secondary cell that is used to power laptop computers.

a. What is the difference between a primary and secondary cell? 1 MARK

b. In lithium-ion cells, lithium ions move between the electrodes as the cell is discharged and recharged. The negative electrode consists of lithiated graphite, LiC_6, and the positive electrode consists of lithium cobalt oxide, $LiCoO_2$. The chemical reactions that take place in the lithium-ion cell are complex. The following equations present a simplified description of the reactions that occur at the electrodes as the cell is **recharged**.

Positive electrode $\quad LiCoO_2 \rightarrow CoO_2 + Li^+ + e^-$

Negative electrode $\quad 6C + Li^+ + e^- \rightarrow LiC_6$



Consider the diagram shown. While the cell is **discharging**, indicate the direction of

i. The movement of electrons, e^- through the wire. 1 MARK

ii. The movement of lithium ions, Li^+ through the electrolyte. 1 MARK

Adapted from VCAA 2010 Exam 2 Short answer Q7

Question 14 (1 MARK)

The reaction shown represents the discharge cycle of a standard lead-acid rechargeable car battery.

$Pb(s) + PbO_2(s) + 4H^+(aq) + 2SO_4^{2-}(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$

During the recharge cycle, the pH of the electrolyte

A. increases and solid Pb is a reactant.

B. increases and solid PbO_2 is produced.

C. decreases and chemical energy is converted to electrical energy.

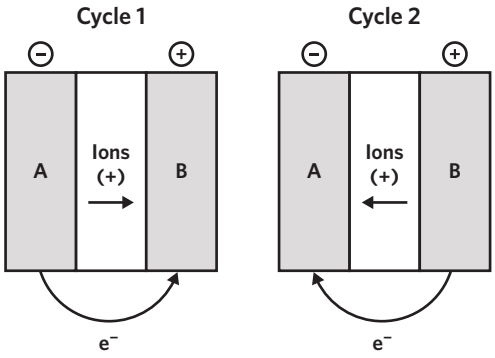
D. decreases and electrical energy is converted to chemical energy.

VCAA 2017 exam Multiple choice Q20

Question 15 (1 MARK)

The diagrams shown represent the operation of a secondary cell during recharge and discharge, in no particular order. The diagrams of the circuits are not complete.

Which of the options below correctly describes the cell and its operation?

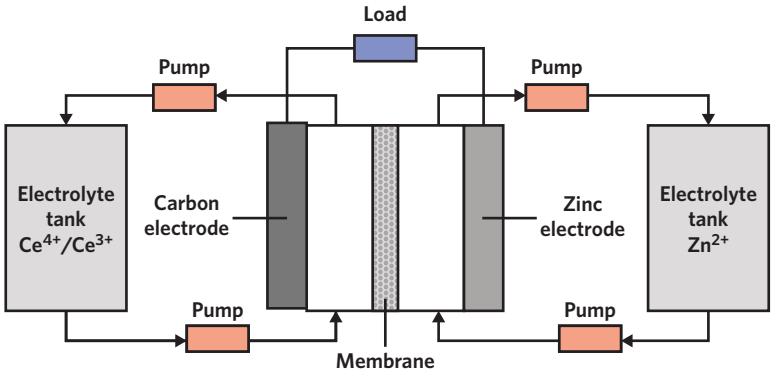


	Cycle 1	Cycle 2
A.	Energy produced	Anode is positive
B.	Spontaneous reaction	Energy produced
C.	Anode is positive	Energy required
D.	Spontaneous reaction	Cathode is positive

VCAA (NHT) 2018 exam Multiple choice Q29

Question 16 (8 MARKS)

The zinc-cerium battery is a commercial rechargeable battery that comprises a series of cells. During recharge, the cells use energy from wind farms or solar cell panels.



During discharge, energy is supplied to electric grids in order to power local factories and homes. The electrolytes are stored in separate storage tanks, and are pumped into and out of each cell when in use. A membrane separates the two electrodes that are immersed in 1 M methanesulfonic acid, CH_3SO_3H. A diagram representing a zinc–cerium cell is shown.

The following half-cell reactions occur in the zinc-cerium cell.

$Zn(CH_3SO_3)_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons Zn(s) + 2CH_3SO_3H(aq)$ $\quad E^0 = -0.76\ V$

$Ce(CH_3SO_3)_4(aq) + H^+(aq) + e^- \rightleftharpoons Ce(CH_3SO_3)_3(aq) + CH_3SO_3H(aq)$ $\quad E^0 = +1.64\ V$

a. Write the equation for the overall discharge reaction. 1 MARK

b. Identify the oxidising agent during discharge and justify your answer using oxidation states. 2 MARKS

c. Determine the theoretical voltage produced by a single cell as it discharges. 1 MARK

d. Write the ionic equation for the reaction occurring at the positive electrode during recharge. 1 MARK

e. Other than transporting ions between electrodes, describe one function of the membrane in the zinc-cerium cell. 1 MARK

f. Specify **one** factor that would limit the life of the zinc-cerium cell. 1 MARK

g. Experts have regarded the zinc-cerium cell as a hybrid of a fuel cell and a secondary cell. Why would this be the case? 1 MARK

VCAA 2019 exam Short answer Q7

Key science skills

Question 17 (1 MARK)

Consider the following half-cells in a secondary cell.

$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons 4OH^-(aq)$ $\quad E^0 = +0.40\ V$

$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$ $\quad E^0 = -0.25\ V$

To how many significant figures should the calculated predicted cell voltage during discharge be expressed?

A. 1

B. 2

C. 3

D. 4

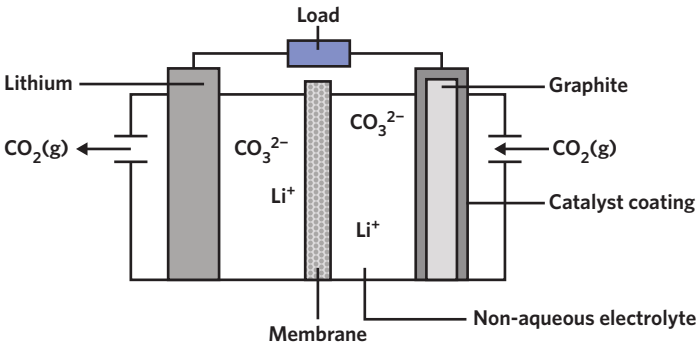
Adapted from VCAA 2013 exam Multiple choice Q1

FROM LESSON 12E

Question 18 (7 MARKS)

Research scientists are developing a rechargeable lithium-carbon dioxide, Li-CO_2 battery. The rechargeable Li-CO_2 battery is made of lithium metal, carbon in the form of graphite (coated with a catalyst) and a non-aqueous electrolyte that absorbs CO_2.

A diagram of the rechargeable Li-CO_2 cell is shown. One Li-CO_2 cell generates 4.5 V.



a. When the Li-CO_2 cell generates electricity, the two half-cell reactions are

$4Li^+ + 3CO_2 + 4e^- \rightarrow 2Li_2CO_3 + C$

$Li \rightarrow Li^+ + e^-$

Write the equation for the overall recharge reaction. States are not required. 1 MARK

b. During discharge, lithium carbonate, Li_2CO_3, deposits break away from the electrode. Describe how this might affect the performance of the battery. 2 MARKS

c. Explain why it is unsafe to use an aqueous electrolyte in the design of the Li-CO_2 battery. Include appropriate equations in your answer. 3 MARKS

d. Could the Li-CO_2 battery be used to reduce the amount of CO_2(g) in the atmosphere? Give your reasoning. 1 MARK

VCAA 2020 exam Short answer Q4

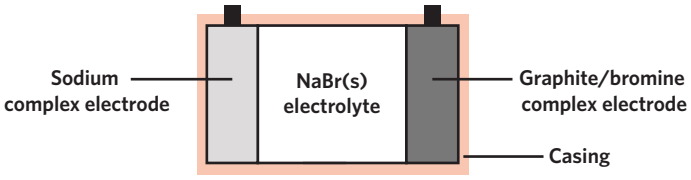
FROM LESSON 12B

Question 19 (6 MARKS)

Lithium-ion rechargeable batteries are very convenient and are widely used in portable electronic devices. However, there are some issues with the ongoing use of these rechargeable batteries, such as the limited availability and the high cost of lithium metal. Another concern is the fires and burns that have resulted from malfunctions occurring during the recharging of some lithium-ion batteries.

Alternative materials to lithium for use in rechargeable batteries are currently being researched and developed. One renewable energy technology company conducted an online competition calling for new and innovative ideas for rechargeable batteries. The submissions required only a labelled diagram of the battery, including all of the essential components, as well as the equations for the reactions that would be expected to occur.

A start-up company submitted the following design for a rechargeable battery.



Half-reactions for the hypothetical rechargeable battery (HRB):

$Na \rightleftharpoons Na^+ + e^-$

$Br_2 + 2e^- \rightleftharpoons 2Br^-$

Melting point of NaBr	747 °C
Melting point of Na	98 °C
Boiling point of Br_2	59 °C

a. Solid sodium bromide, NaBr, has been chosen as the electrolyte for the HRB. Is this a suitable electrolyte? Justify your answer. In your response, refer to the essential requirements of an electrolyte. 3 MARKS

b. Discuss improvements that could be made to the HRB. Your response should be based on chemical principles rather than financial or environmental concerns. 3 MARKS

In your response:

- Suggest and justify a specific improvement to the HRB.
- Comment on a safety implication of the material(s) used in your improved version of the HRB.

Adapted from VCAA (NHT) 2019 exam Short answer Q9

FROM LESSONS 12B & 12E

Questions from multiple lessons

Question 20 (2 MARKS)

Lina is at the beach with their friends and has their phone sitting out in the sun while they go in the water for a swim. When Lina gets back to their phone after 10 minutes they notice that the battery life of their phone has dropped significantly. Explain why this is the case.

FROM LESSON 4A

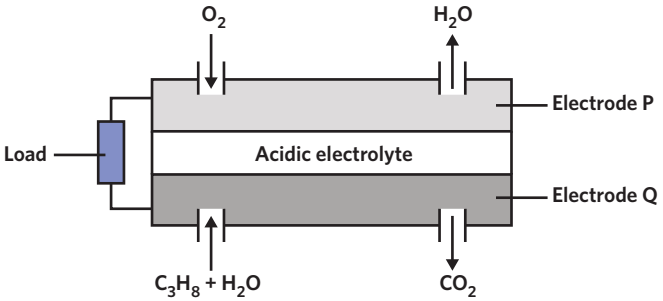
Question 21 (8 MARKS)

Liquefied petroleum gas (LPG) is a type of fuel currently used in some cars.

a. The main component of LPG is propane, C_3H_8, gas. Write a thermochemical equation for the complete combustion of propane gas. 2 MARKS

b. An LPG-powered car uses 33.7 L of C_3H_8 to travel 270 km. Calculate the amount of energy released when 33.7 L of C_3H_8 undergoes complete combustion. The density of C_3H_8 is 0.510 kg L^{-1}. 2 MARKS

c. A diagram of an acidic LPG fuel cell is shown.



i. State the polarity of Electrode P. 1 MARK

ii. Write a balanced half-equation for the reaction at Electrode Q. States are not required. 2 MARKS

iii. Identify **one** difference between an acidic LPG fuel cell and a secondary cell during discharge. 1 MARK

VCAA 2022 exam Short answer Q7

FROM LESSONS 1D, 2A & 3E

6D Designing cells to produce green hydrogen



Image: Scharfsinn/Shutterstock.com

Why is green hydrogen potentially a sustainable energy supply of the future?

Green hydrogen has the potential to become a critical component of the future energy mix, as green hydrogen produces zero greenhouse gas emissions during the production process. This makes it a vital tool in reducing, and eventually eliminating, our carbon footprint. In this lesson we will learn what green hydrogen is and how redox cells are designed to maximise its production whilst minimising its environmental impact.

KEY TERMS AND DEFINITIONS

Artificial photosynthesis process that utilises human-made materials to capture sunlight and split water molecules to create hydrogen and oxygen

Electrolyser a device or system that houses the process of electrolysis and manages the process flow of inputs and outputs

Green hydrogen hydrogen gas produced using renewable energy sources, such as wind or solar power, through electrolysis

Photovoltaics conversion of solar energy to electrical energy using human-made materials

Polymer electrolyte membrane (PEM) also called proton exchange membrane, uses a proton-conducting polymer membrane as the electrolyte and connects two half-cells, but prevents the mixing of different molecules

STUDY DESIGN DOT POINT

- the role of innovation in designing cells to meet society's energy needs in terms of producing 'green' hydrogen (including equations in acidic conditions) using the following methods:
  - polymer electrolyte membrane electrolysis powered by either photovoltaic (solar) or wind energy
  - artificial photosynthesis using a water oxidation and proton reduction catalyst system

6A 6B 6C **6D** 6E

- 3.2.13.1 Green hydrogen
- 3.2.13.2 Polymer electrolyte membrane (PEM) electrolysis
- 3.2.13.3 Artificial photosynthesis

ESSENTIAL PRIOR KNOWLEDGE

1B Renewability
1B Sustainability
1C Photosynthesis

See questions 55–57.

Green hydrogen 3.2.13.1

The different methods of hydrogen production are now colour coded. These different colours help inform the carbon intensity and environmental impact associated with hydrogen production, with green hydrogen being the most favourable in terms of clean energy transition.

Why is green hydrogen the best for our planet?

As was discussed in lesson 5D, the production of hydrogen is now classified by a colour according to its source.[1] The brighter colours (figure 1) represent energy sources and processes with lower greenhouse gas emissions, while the darker colours represent higher emissions and a larger carbon footprint.

KEEN TO INVESTIGATE?

[1] **What exactly do the different colours of hydrogen represent?** Search YouTube: The colours of hydrogen

Green	Blue	Turquoise	Purple/pink	Black/brown	Grey	White
Produced using renewable energy sources, such as solar or wind power, through the use of an electrolyser.	Produced from natural gas using a process called steam reforming.	Produced by using natural gas as a feedstock, which is broken down into hydrogen and solid carbon.	Produced using nuclear power.	Produced from black coal (black hydrogen) and brown coal (brown hydrogen) via gasification.	Produced from natural gas using steam reforming.	Extracted from naturally occurring underground deposits.
It has no carbon emissions and is considered the cleanest form of hydrogen.	The carbon dioxide emitted during production is captured and stored.	It is considered 'low carbon' as the process does not emit carbon dioxide, but there can be emissions associated with the mining and transport of natural gas.	Spent nuclear fuel is difficult to store.	Gasification releases carbon monoxide and dioxide as a by-product into the atmosphere.	In this case, relevant technologies do not capture resulting emissions. Instead, they are released into the atmosphere.	It is considered 'low carbon' as the process does not emit carbon dioxide, but there can be emissions associated with the mining and transport of natural gas.

Figure 1 The characteristics of the production of the different colours of hydrogen

Green hydrogen is a form of hydrogen fuel that is produced through the process of electrolysis using renewable energy sources. The hydrogen produced is referred to as 'green' due to its association with renewable energy sources. The source of energy used for the electrolysis process can vary from solar power, wind power, hydroelectricity or biomass, which means that the process of producing green hydrogen does not produce any emissions or release any greenhouse gases into the atmosphere. This makes green hydrogen an important factor in the fight against climate change. It can be used as a clean and sustainable fuel for a variety of applications including transportation, industry, and power generation (figure 2).

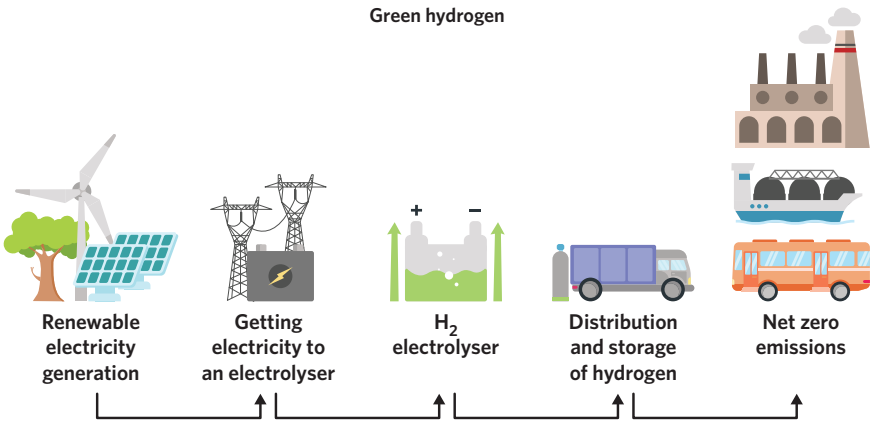


Figure 2 An overview of the production, distribution, and uses of green hydrogen

Currently, the cost of renewable energy sources needed to produce green hydrogen such as solar or wind is still relatively high, and **electrolysers** have limited efficiency and economic feasibility for large-scale production. However, as technology advances and the cost of renewable energy sources continues to decrease, it is expected that the production of green hydrogen will become more economically feasible and commercially viable. This will also contribute to the reduction of greenhouse gas emissions and a shift towards more sustainable energy sources. Even though green hydrogen is the ultimate goal, other types of hydrogen are still of use in Australia's move towards cleaner and greener energy.

PROGRESS QUESTIONS

Question 1

Hydrogen is classified as green when it is produced from

A. reusable resources.
B. renewable resources.
C. recyclable resources.
D. non-renewable resources.

Question 2

What are possible current limitations to the large-scale production of green hydrogen?

A. Availability of resources
B. Number of filling stations
C. Not enough demand
D. Cost

Question 3

Which of the following is an example of how hydrogen could be used in the very near future to help Australia's move towards a cleaner, greener utilisation of energy?

A. Adding a small amount of green hydrogen (10%) into the domestic gas supply
B. Setting up green hydrogen fuelling stations all around the country
C. Making all car manufacturers produce hydrogen powered cars
D. Stopping the production of electric vehicles

Polymer electrolyte membrane (PEM) electrolysis 3.2.13.2

A **polymer electrolyte membrane (PEM)**, also known as a polymer exchange membrane, connects two half-cells by allowing them to exchange protons between two electrodes, but prevents the mixing of the contents of the two chambers. When the source of energy used for this electrolytic process is solar power, wind power, hydroelectricity, or biomass, it can produce green hydrogen (and oxygen).

How does a polymer electrolyte membrane (PEM) function?

A PEM is a critical component in many electrolysis processes, including green hydrogen electrolysis. In a green hydrogen electrolyser, the PEM, which is made from a plastic polymer, helps to separate the electrons and gases (at a temperature range of 20–80 °C) produced during the electrolysis process (figure 3).

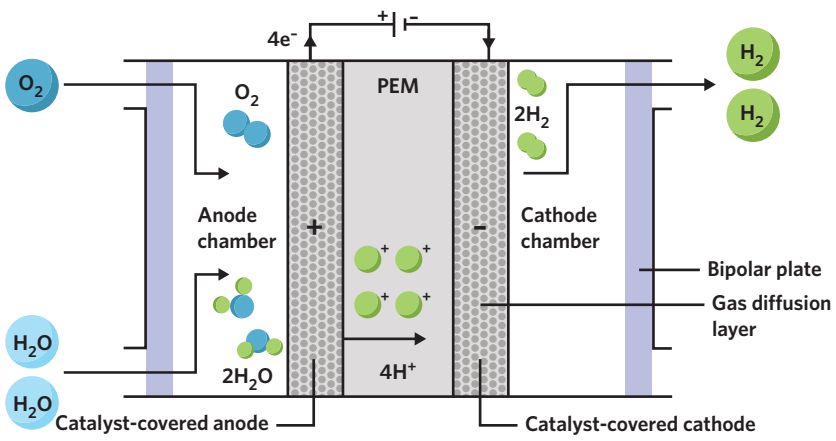


Figure 3 Typical acid electrolyser cell design used to produce green hydrogen

MISCONCEPTION

'Electroysers make the production of green hydrogen carbon neutral.'

The actual chemical process of electrolysis is carbon neutral; however, all the technology and chemicals required produce carbon emissions in their manufacture and transportation.

Electrolyser cell design features:

- The electrodes are typically covered with a platinum catalyst, which increases the rate of production of the gases.
- Gas diffusion layers made up of gold-lined, titanium and carbon paper help distribute the reactant gases evenly across the surface of the electrodes.
- Bipolar plates prevent the build up of current and provide mechanical support for the electrolyser.

PEM design functions in the electrolyser cell:

- It is selectively permeable (plastic polymer) to protons and does not conduct electrons, which means it only allows the flow of protons, but blocks the flow of other ions (oxide or impurities) and electrons.
- It is placed between the two electrodes, where it acts as a barrier, blocking the passage of water, hydrogen, and oxygen molecules.
- Overall, the PEM helps to ensure that the hydrogen and oxygen gases are produced separately, making the process more efficient and reducing the possibility of contamination or mixing of the gases.

Reactions occurring during electrolysis:

- Oxidation half-equation at the anode: $2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^-$
  At the anode oxygen gas is produced when oxide ions are oxidised, which can be sold as medical grade oxygen.
- Reduction half-equation at the cathode: $4H^+(aq) + 4e^- \rightarrow 2H_2(g)$
  The hydrogen ions produced during the electrolysis of water react with the electrons at the cathode to produce hydrogen gas, which is collected and stored.
- Overall equation: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$
  An electric current is passed through water, which causes the water molecules to split into hydrogen and oxygen gases.

The design of the PEM cell considers many of the important green chemistry principles: catalysis, designing safer chemicals, prevention of wastes, and the use of renewable feedstocks. This type of (acid) electrolyser is used in a variety of applications including fuel cell cars and renewable energy storage systems. Alkaline electrolysers are also available and both types have their advantages and disadvantages.

WORKED EXAMPLE 1

Which of the following is **not** a design function of the polymer electrolyte membrane (PEM)?

A. Conduction of ions
B. Conduction of electrons
C. Conduction of protons
D. Separation of molecules

What information is presented in the question?

Possible properties of the proton electrolyte membrane.

What is the question asking us to do?

Select the property that is not a design function of the PEM.

What strategies do we need in order to answer the question?

1. Recall that conduction is when a charge flows.
2. Recall where the different charges flow.

Answer

Option A: Hydrogen ions (protons) pass through the membrane.

Option B: Electrons are part of the external circuit not the internal circuit, which is where the PEM is located. The PEM does not conduct electrons as it is made of a plastic polymer.

Option C: Hydrogen ions (protons) pass through the membrane.

Option D: The PEM is a physical barrier that prevents electrons, water, and hydrogen molecules from passing through it.

PROGRESS QUESTIONS

Question 4

Why should distilled or desalinated water be used in the electrolyser instead of ionised water?

A. Other ions from the ionised water could be reduced, decreasing the efficiency of the process.

B. Other ions from the ionised water could be reduced, increasing the efficiency of the process.

C. Distilled or desalinated water is cheaper than normal ionised water.

D. Ionised water is cheaper than distilled or desalinated water.

Question 5

Why is the PEM electrolyser used within the temperature range of 20–80 °C?

A. Water must be a solid.

B. Water must be a liquid.

C. Water must be a gas.

D. None of the above.

Artificial photosynthesis 3.2.13.3

The conversion of solar energy directly to electrical energy is termed **photovoltaics**, whereas the conversion of sunlight, water and carbon dioxide into carbohydrates and oxygen is called photosynthesis (lesson 1C). The efficiency of plant photosynthesis, that is, the proportion of light energy converted into chemical energy, is less than 1%.

How does artificial photosynthesis work?

Artificial photosynthesis follows a similar process to photosynthesis, but uses human-made materials to capture sunlight and split water molecules to create hydrogen and oxygen (figure 4). This is typically done using semiconductor materials, combined with catalysts to facilitate the chemical reaction.

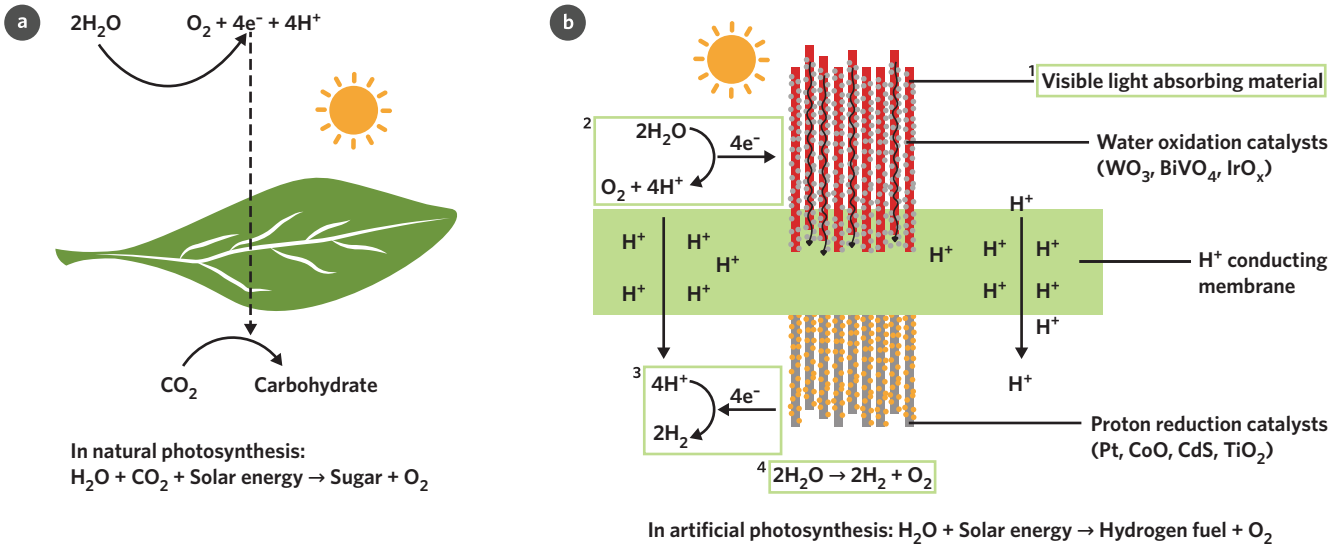


Figure 4 Comparison between the stages of **(a)** natural and **(b)** artificial photosynthesis

An artificial photosynthesis cell design has electrodes (nanowires) that are typically covered with a variety of different catalysts which increases the rate of production of the gases. The design functions in the artificial photosynthetic cell and the reactions occurring during electrolysis are very similar to the PEM electrolyser cell.

Unlike plant photosynthesis, which releases sugars and oxygen, artificial photosynthesis is required to create energy rich industrial fuels. Hydrogen is the primary solar fuel produced (oxygen is also produced), and can be used in various ways. Hydrogen can be used:

- as a liquid energy source for fuel cells
- as a fuel source in combustion engines
- to reduce carbon dioxide to methanoic acid in the presence of a catalyst
- to reduce carbon dioxide to methanol in the presence of a catalyst
- to reduce carbon dioxide to methane in the presence of a catalyst
- to reduce nitrogen gas to ammonia in the presence of a catalyst.

Artificial photosynthesis is a series of redox reactions (in acidic conditions) that can be summarised into four stages (figure 4):

1. Light harvesting system: materials that are able to absorb light promote electrons to a higher energy state which produces around 2 V, the amount of electrical energy required to drive the reactions.
2. Water oxidation in acid and using catalysts: $2H_2O(l) \rightarrow 4H^+ + O_2(g) + 4e^-$
3. Proton reduction in the presence of catalysts: $4H^+ + 4e^- \rightarrow 2H_2(g)$
4. Overall: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

These steps result in the creation of green hydrogen, which can be used in the reduction of $CO_2(g)$ or $N_2(g)$ in the presence of specific catalysts, shown in the following examples:

$CO_2(g) + H_2(g) \rightarrow HCOOH(l)$

$CO_2(g) + 3H_2(g) \rightarrow CH_3OH(l) + H_2O(l)$

$CO_2(g) + 4H_2(g) \rightarrow CH_4(g) + 2H_2O(l)$

$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$

These compounds are a store of chemical energy and can be used as industrial fuels or starting materials for other consumer products.

The advantages of creating fuels through artificial photosynthesis are numerous:

- The process does not create greenhouse gases (liquid water is produced).
- The process does not require the use of fossil fuels.
- The process can remove carbon dioxide from the atmosphere.
- The process produces oxygen as a by-product.
- The process can create and store energy in more than one type of hydrocarbon fuel.
- The process can create green ammonia by reacting hydrogen produced with $N_2(g)$ from air, which is used to manufacture fertilisers.

Artificial photosynthesis has the potential to be a game changer in the fight against climate change, as it can provide a sustainable and renewable source of fuel that does not depend on fossil fuels. However, there are still many challenges to be overcome, such as reducing the cost of materials and scaling up the technology to be used on a larger scale. It is still in the early stages of development, but it has the potential to play a major role in achieving a cleaner energy future.

How sustainable is green hydrogen?

Green hydrogen is a flexible energy source that can be used in a variety of applications, including power generation, transportation, and industrial processes. However, there are also some challenges to consider when it comes to the sustainability of using green hydrogen as a fuel. Some of these challenges include:

- Energy Efficiency: The process of producing green hydrogen can be energy-intensive, especially when using renewable energy sources that are costly to implement. This can reduce the overall efficiency of the process and increase costs.
- Infrastructure: There is currently limited infrastructure for producing, storing, and transporting hydrogen. This can make it challenging to scale up the use of hydrogen as a fuel source.
- Cost: Currently, the cost of green hydrogen production is higher than that of other conventional fuels. This can limit its use, especially in developing countries.
- Water Resources: Hydrogen production requires significant amounts of water, which can be a challenge in areas facing water scarcity or drought.

Overall, the sustainability of using green hydrogen as a fuel source depends on how it is produced and implemented. With the right investment in technology and infrastructure, it has the potential to be a crucial part of a sustainable cleaner energy future.

PROGRESS QUESTIONS

Question 6

What type of reaction occurs in both natural and artificial photosynthesis?

A. Displacement
B. Combustion
C. Respiration
D. Redox

Question 7

The primary solar fuel produced from artificial photosynthesis is

A. a hydrocarbon.
B. carbon dioxide.
C. hydrogen.
D. crude oil.

Question 8

Hydrogen acts as a(n) _____ when reacting with nitrogen or carbon dioxide to produce energy-rich compounds.

A. oxidising agent
B. reducing agent
C. acid
D. base

Theory summary

- Green hydrogen is produced using renewable energy sources, such as solar or wind power, through the use of an electrolyser.
- The production of green hydrogen has no carbon emissions, so green hydrogen is considered the cleanest form of hydrogen.
- PEM electrolysers have many design features used to maximise the production of green hydrogen, including:
  - electrodes that are typically covered with a platinum catalyst, which increases the rate of production of the gases
  - gas diffusion layers made up of gold-lined, titanium and carbon paper to help distribute the reactant gases evenly across the surface of the electrodes
  - bipolar plates that prevent the build up of the current and provide mechanical support for the electrolyser
  - a polymer electrolyte membrane that is selectively permeable to protons and does not conduct electrons, and acts as a physical barrier that only allows positively charged (proton) ions to pass through
  - keeps the two gases separated during the electrolysis process.
- PEM electrolyser cell reactions (in acid):
  - Oxidation: $2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^-$
  - Reduction: $4H^+(aq) + 4e^- \rightarrow 2H_2(g)$
  - Overall: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$
- Artificial photosynthesis uses human-made materials to capture sunlight and split water molecules to create hydrogen and oxygen.
- Catalysts play a crucial role in splitting the water molecules by facilitating the reaction.
- Artificial photosynthesis reactions (in acid):
  - Water oxidation in the presence of catalysts: $2H_2O(l) \rightarrow 4H^+ + O_2(g) + 4e^-$
  - Proton reduction in the presence of catalysts: $4H^+ + 4e^- \rightarrow 2H_2(g)$
  - Overall: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$
- The primary solar fuel produced from artificial photosynthesis is green hydrogen, which is used to reduce $CO_2(g)$ and $N_2(g)$ in the presence of specific catalysts to produce other useful energy rich molecules like $HCOOH(l)$, $CH_3OH(l)$, $CH_4(g)$, and $NH_3(g)$.
- The advantages of creating fuels through artificial photosynthesis are numerous.
- The sustainability of using green hydrogen as an energy source depends on how it is produced and implemented.

6D Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 9–12.

The PEM electrolyser cell and artificial photosynthesis cell both utilise water.

Question 9 (1 MARK)

What are the reaction conditions in both cells?

A. Alkaline **B.** Acidic **C.** Basic **D.** Neutral

Question 10 (1 MARK)

Which of the following equations represents the oxidation of water in acidic conditions?

A. $2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^-$

B. $4H^+(aq) + O_2(g) + 4e^- \rightarrow 2H_2O(l)$

C. $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

D. $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

Question 11 (1 MARK)

Which of the following equations represents the reduction of a proton?

A. $2H_2 \rightarrow 4H^+ + 4e^-$

B. $4H^+ + 4e^- \rightarrow 2H_2$

C. $2O^{2-} \rightarrow O_2 + 4e^-$

D. $O_2 + 4e^- \rightarrow 2O^{2-}$

Question 12 (1 MARK)

Give the balanced equation for the overall reaction occurring in the two types of cells.

Exam-style

Question 13 (2 MARKS)

The efficiency of photosynthesis in most plants is usually below 1%. In contrast, the highest reported efficiency for artificial photosynthetic prototypes is around 22%. Given the potential improvement in the efficiency of artificial photosynthesis, what are two possible challenges that are currently preventing its mainstream use?

Question 14 (4 MARKS)

Both a PEM electrolyser cell and artificial photosynthesis cell can be utilised to produce green hydrogen. When comparing the design of each cell, explain two similarities and two differences in their function.

Key science skills

Question 15 (6 MARKS)

Using the chemistry that you have studied, discuss the carbon neutrality and sustainability of using PEM electrolyser cells to produce green hydrogen for use as a fuel for transport.
Use the following headings in your answers:

a. Carbon dioxide 2 MARKS

b. Sustainability of using green hydrogen 2 MARKS

c. Using green hydrogen as a fuel for vehicle transport 2 MARKS

FROM LESSON 12E

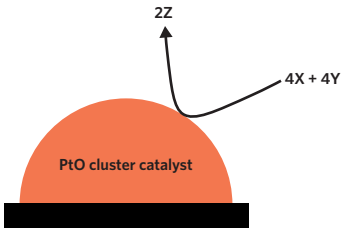
Questions from multiple lessons

Question 16 🌶🌶 (6 MARKS)

Catalysis plays an important role in the use of artificial photosynthesis to produce green hydrogen.

a. Explain the role of catalysts in the artificial photosynthesis process, focusing on how they increase the rate of specific reactions. Give reference to specific equations in your answer. 3 MARKS

b. The diagram shown demonstrates the use of platinum(II) oxide clusters as proton reduction catalysts.



Identify the chemical species represented by X, Y and Z in the diagram. 3 MARKS

FROM LESSON 4B

Question 17 🌶🌶🌶 (9 MARKS)

Consider a PEM electrolyser, which facilitates the following electrolysis half-reactions under acidic conditions.

Oxidation: $2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^-$

Reduction: $2H^+(aq) + 2e^- \rightarrow H_2(g)$

a. What is the voltage input required for the overall reaction to occur? 1 MARK

b. In lesson 2B, the formula $q = VIt$ was introduced, where q is a quantity of energy (in joules, J), V is a voltage (in Volts, V), I is a current (in amperes, A), and t is a quantity of time (in seconds, s). Use this formula to calculate the minimum energy input required to operate this electrolyser, assuming a current of 2.00 A runs through the external circuit for 2 hours. Express your answer in kJ. 1 MARK

c. Faraday's Laws can also be applied to electrolysers. How many moles of green hydrogen would theoretically be produced during this reaction? 3 MARKS

d. The same half-reactions occur during artificial photosynthesis, but no external power source is involved. Where do the reactants get this energy from? 1 MARK

e. An engineer wishes to power the PEM electrolyser using energy produced during the combustion of octane. Assuming 40% of the energy produced in this reaction is lost, at least what mass of octane must be combusted? 3 MARKS

FROM LESSONS 1C, 1D, 2A, 2B, 3F & 6B

Back to contents

6E Faraday's Laws in electrolytic cells



How does electrolysis destroy water pipes connected to the tram and train network?

When trams or trains travel along steel tracks, the electricity these tracks carry may leak underground and be conducted by metal water pipes, forming an electrolytic cell. Over sufficiently long periods of time, this causes the metal pipes (acting as the anode) to decrease in mass, creating small holes and big problems for underground water systems. In this lesson, we will explore how quantities – reactant or product amounts, current, and time – can be calculated for electrolytic cells using Faraday's Laws.

KEY TERMS AND DEFINITIONS

Coulomb unit of electric charge (equal to the quantity of charge carried by a current of 1 ampere in 1 second)

Electric charge property of matter carried by current and measured in coulombs, where the charge on a single electron is -1.60×10^{-19} coulombs

Faraday constant (*F*) charge on one mole of charged particles, equal to 96 500 coulombs per mole

STUDY DESIGN DOT POINT

- the application of Faraday's Laws and stoichiometry to determine the quantity of electrolytic reactant and product, and the current or time required to either use a particular quantity of reactant or produce a particular quantity of product

6A 6B 6C 6D 6E

3.2.14.1 Applying Faraday's Laws in electrolytic cells

3.2.14.2 Combining Faraday's Laws in electrolytic cells

ESSENTIAL PRIOR KNOWLEDGE

2A Stoichiometry

6B Electrolytic cells

See questions 58–59.

Applying Faraday's Laws in electrolytic cells 3.2.14.1

Faraday's Laws of electrolysis are introduced in detail in lesson 3F.

How do Faraday's Laws apply to electrolytic cells?

In the context of electrolytic cells, Faraday's Laws are as follows:

- Faraday's First Law states that the mass deposited or produced at the cathode, or lost or consumed at the anode (m, in grams) of a given galvanic cell is directly proportional to the quantity of **electric charge** (Q, in **coulombs**) carried by the cell; in other words, $m \propto Q$.

USEFUL TIP

Equivalently, Faraday's Second Law states that y moles of electrons ($n(e^-)$) are required for 1 mole of substance to be lost or consumed at the anode, where y is the coefficient of electrons in the balanced oxidation half-equation occurring in the cell.

- Faraday's Second Law states that x moles of electrons ($n(e^-)$) are required to deposit or produce 1 mole of substance at the cathode, where x is the coefficient of electrons in the balanced reduction half-equation occurring in the cell.
  For example, consider the following reduction half-equations:
  $Ag^+(aq) + e^- \rightarrow Ag(s)$
  $Sn^{2+}(aq) + 2e^- \rightarrow Sn(s)$
  To deposit 1 mole of silver at the cathode, 1 mol of electrons is required, whereas to deposit 1 mole of tin at the cathode, 2 mol of electrons is required.

PROGRESS QUESTIONS

Question 1

In an electrolytic cell, the cathode half-reaction is as follows.

$Cr^{3+}(aq) + 3e^- \rightarrow Cr(s)$

If 1.0 mol of electrons is passed through this cell, how many moles of chromium metal are formed?

A. 0.33 mol
B. 1.0 mol
C. 3.0 mol
D. 52.0 mol

Combining Faraday's Laws in electrolytic cells 3.2.14.2

As in lesson 3F, Faraday's Laws can be combined with stoichiometric methods (introduced in lesson 2A) and other relationships to calculate quantities in electrolytic cells.

How can we calculate quantities in electrolytic cells?

Recall from lesson 3F that the quantity of charge carried by an electrochemical cell (be it galvanic, fuel, or electrolytic) can be calculated using the formula $Q = It$, where Q is the quantity of electrical charge in coulombs (C), I is the current in amperes (A), and t is the time in seconds (s).

Also recall that Faraday's laws combine to give the formula $n(e^-) = \frac{Q}{F}$, where $n(e^-)$ is the number of moles of electrons passing through the external circuit of the electrochemical cell (in mol), Q is the quantity of charge carried (in coulombs, C), and $F = 96\,500$ C mol^{-1} is the **Faraday constant**.

Finally, recall from lesson 2A the formula $n = \frac{m}{M}$, which can be used to convert between masses of substances in electrolytic cells, and the formula $n = \frac{V}{V_m}$, which can be used to convert between volumes of substances in electrolytic cells under standard laboratory conditions.

USEFUL TIP

Refer to lesson 3F figure 2 for a flowchart outlining all calculation steps involved in Faraday's Laws questions.

These four formulas are given in the VCE Data Book, and can be applied to electrolytic cells to calculate:

- the mass and/or volume decrease at the anode
- the mass and/or volume increase at the cathode
- the current required to consume a given quantity of reactant or produce a given amount of product
- the time required to consume a given quantity of reactant or produce a given amount of product.

One common application of Faraday's Laws is to construct electroplating cells, which have been explored in lesson 6B. For example, a manufacturer may be looking to electroplate a spoon with a 10 g layer of silver. These formulas can be used to calculate the time this electroplating process will take, and a possible setup for this experiment is shown in figure 1.

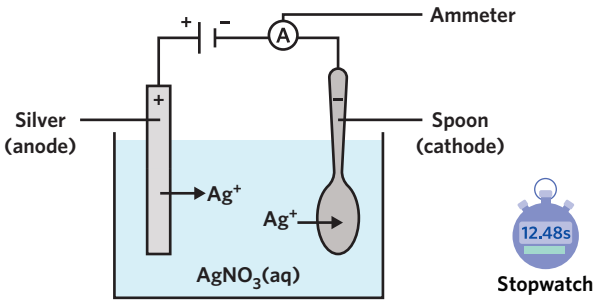
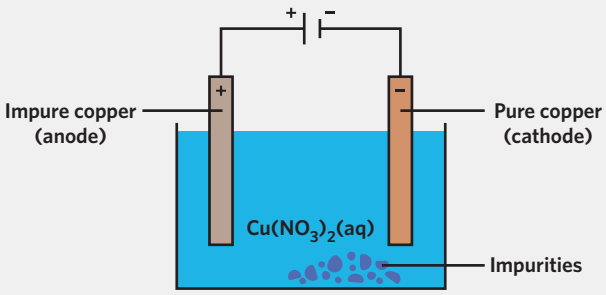


Figure 1 Electroplating apparatus used for Faraday's Laws calculations

Another industry application is electrorefining, whereby an impure sample of a metal is purified using an electrolytic cell. Worked example 1 demonstrates how a mining company could calculate the current required to produce 10 kg of pure copper from an impure sample in 24 hours.

WORKED EXAMPLE 1

A mining company uses the electrolytic cell shown for its copper electrorefining process (converting impure copper to pure copper).



To meet its performance targets, the company needs each cell to produce 10.0 kg of pure copper in 24.0 hours. What current is required for the company to meet this target?

What information is presented in the question?

A diagram of the electrolytic cell.

The cell produces 10.0 kg of pure copper.

The cell operates for 24.0 hours.

What is the question asking us to do?

Calculate the current of the electrolytic cell.

What strategies do we need in order to answer the question?

1. Determine the reduction half-equation.
2. Convert the mass produced to grams.
3. Calculate the number of moles of copper deposited using $n = \frac{m}{M}$.
4. Calculate the number of moles of electrons using stoichiometric ratios.
5. Calculate the total charge carried using $n(e^-) = \frac{Q}{F}$.
6. Convert the time of operation to seconds.
7. Calculate the current using $Q = It$.

Continues →

Answer

Pure copper is produced at the cathode according to the half-equation

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

$m(\text{Cu produced}) = 10.0 \text{ kg}$

$m(\text{Cu produced}) = 10.0 \times 10^3 \text{ g}$

$n(\text{Cu produced}) = \frac{m}{M}$

$n(\text{Cu produced}) = \frac{10.0 \times 10^3 \text{ g}}{63.5 \text{ g mol}^{-1}}$

$n(\text{Cu produced}) = 1.5748 \times 10^2 \text{ mol}$

$n(e^-) : n(\text{Cu})$

$2 \quad : \quad 1$

$n(e^-) = 2 \times n(\text{Cu})$

$n(e^-) = 2 \times (1.5748 \times 10^2 \text{ mol})$

$n(e^-) = 3.1496 \times 10^2 \text{ mol}$

$Q = n(e^-) \times F$

$Q = 3.1496 \times 10^2 \text{ mol} \times 96\,500 \text{ C mol}^{-1}$

$Q = 3.03937 \times 10^7 \text{ C}$

$t = 24.0 \text{ hours}$

$t = (24.0 \times 60 \times 60) \text{ s}$

$t = 86\,400 \text{ s}$

$I = \frac{Q}{t}$

$I = \frac{3.03937 \times 10^7 \text{ C}}{86\,400 \text{ s}}$

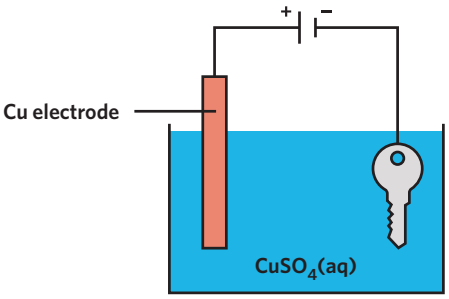
$I = 351.78 \text{ A}$

Therefore, the current required is 352 A (3 sig. figs).

PROGRESS QUESTIONS

Use the following information to answer questions 2–3.

Lilianka used an electrolytic cell to electroplate a key with copper, but lost track of time.



They know that the average current throughout their experiment was 2.00 A, and they calculate that 1554 C of charge was carried by the cell during the experiment.

Question 2

For how long was their electrolytic cell in operation?

A. 13 s **B.** 777 s **C.** 1554 s **D.** 3108 s

Question 3

Based on the values given, what mass of copper was formed at the cathode, assuming copper is reduced according to the half-equation $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$?

A. 0.511 g **B.** 1.02 g **C.** 8.05 g **D.** 63.5 g

Question 4

An electrolytic cell consumed a charge of 4.00 C in 5.00 minutes. This represents a consumption of

A. 4.15×10^{-5} mol of electrons. **B.** 2.07×10^{-4} mol of electrons.

C. 1.93×10^4 mol of electrons. **D.** 2.41×10^4 mol of electrons.

VCAA 2021 exam Multiple choice Q9

Theory summary

- Faraday's Laws of electrolysis state that:
  - The mass increase at the cathode of an electrolytic cell is directly proportional to the quantity of charge carried.
  - To deposit 1 mole of substance at the cathode, x moles of electrons ($n(e^-)$) are required, where x is the coefficient of electrons in the balanced reduction half-equation occurring in the cell.
- The amount of charge carried by an electrolytic cell, Q (in C), can be calculated using the formula $Q = It$, where I (in A) is the current and t (in seconds) is the time for which the cell operates.
- The number of moles of electrons, $n(e^-)$ (in mol), passing through the external circuit of an electrolytic can be calculated using the formula $n(e^-) = \frac{Q}{F}$, where Q (in C) is charge carried and F is the Faraday constant (96 500 C mol^{-1}).
- Stoichiometry can be combined with these formulas to calculate masses or volumes of products or reactants in electrolytic cells.

6E Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 5–8.

An electroplating cell containing two platinum electrodes and an electroplating solution is operated at 5.0 A for 600 s. After the cell is turned off, 0.54 g of metal is found to have been deposited on the cathode.

Question 5 (1 MARK)

What is the charge carried by this cell?

A. 50 C **B.** 267 C **C.** 300 C **D.** 3000 C

Question 6 (1 MARK)

How many moles of electrons passed through the external circuit of the cell?

A. 0.015544 mol **B.** 0.031088 mol **C.** 0.046632 mol **D.** 0.062176 mol

Question 7 (1 MARK)

Which formula gives the mass of a metal deposited at the cathode in an electrolytic cell, where $+x$ is the charge on the metal cation?

A. $m(\text{metal deposited}) = n(e^-) \times M(\text{metal})$

B. $m(\text{metal deposited}) = x \times n(e^-) \times M(\text{metal})$

C. $m(\text{metal deposited}) = \frac{n(e^-)}{x} \times M(\text{metal})$

D. $m(\text{metal deposited}) = \frac{x}{n(e^-)} \times M(\text{metal})$

Question 8 (1 MARK)

Which electroplating solution was used in this process?

A. 1 M $AgNO_3$

B. 1 M $Ni(NO_3)_2$

C. 1 M $Pb(NO_3)_2$

D. 1 M $Cr(NO_3)_3$

VCAA (NHT) 2018 exam Multiple choice Q24

Exam-style

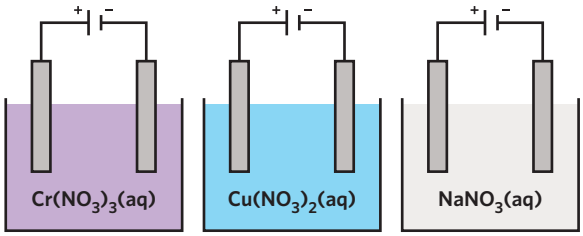
Question 9 (1 MARK)

Gabriella wants to coat a ring in 0.300 g of gold using an electrolytic cell that involves the half-equation $Au^+(aq) + e^- \rightarrow Au(s)$. If a current of 2.00 A is flowing through the cell, what is the minimum time, in seconds, required to complete this process?

A. 55 s **B.** 73 s **C.** 92 s **D.** 153 s

Question 10 (5 MARKS)

Khan wanted to test the effect of the oxidation states of metal ions on the production of three different metals: chromium, copper and sodium. In his experiment, he used 1.0 M solutions of $Cr(NO_3)_3$, $Cu(NO_3)_2$, and $NaNO_3$. He decided to use 0.045 faradays of electric charge (equivalent to 4342.5 coulombs) for all experiments.



a. Determine the amount of metal, in mol, deposited on the cathode of the electrolytic reaction involving chromium(III) nitrate. 2 MARKS

b. Order the three metals by the number of moles of metal deposited (from most to least), during electrolysis involving their corresponding electrolyte. Justify your answer. 3 MARKS

Question 11 (4 MARKS)

As explored in lesson 6D, an acidic electrolytic cell can be used to produce hydrogen gas, H_2, via the following reaction:

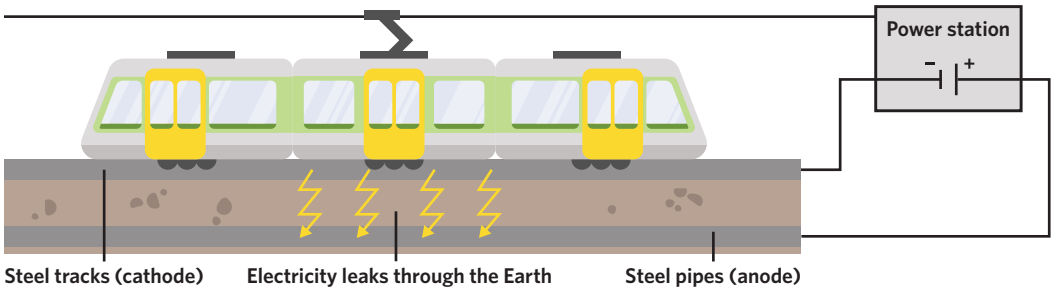
$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

a. Write the half-equation occurring at the cathode in this cell under acidic conditions. 1 MARK

b. If the cell runs for 2.25 hours using a current of 1.60 A, calculate the volume of hydrogen gas produced under standard laboratory conditions (SLC). 3 MARKS

Question 12 (5 MARKS)

Phelin is a tram enthusiast who lives on a road with a major tram line. He learns that when a tram travels along its track, some of its electricity leaks into the ground (the 'electrolyte') and, combined with underground water pipes made of steel (mostly iron), forms an electrolytic cell. This is shown in the diagram.



Over time, this electrolytic process causes these pipes to be oxidised, forming holes that may lead to water leakage. Assume that these pipes are pure iron, Fe, and that iron is completely oxidised to Fe^{3+} ions.

a. Write the balanced oxidation half-equation occurring in this scenario. 1 MARK

b. When a tram passes, for a 3.0 second period, a current of 3.6 A leaks into the metal pipes. What is the minimum number of trams that must pass Phelin's house to cause his pipes to decrease in mass by 5.26 g? Round your answer to a whole number of trams. 4 MARKS

Key science skills

Question 13 🌶🌶🌶 (13 MARKS)

A student designed an experiment to investigate current efficiency during the electrolysis of a sodium chloride, NaCl, solution. Current efficiency is the amount of product produced, expressed as a percentage of the theoretical amount of product, calculated using Faraday's Laws. When the products of an electrolysis are gases, current efficiency can be calculated using the following formula.

$$\text{current efficiency} = \frac{\text{volume of gas produced}}{\text{volume of gas expected based on Faraday's Law}} \times 100\%$$

All experimental work was carried out under standard laboratory conditions (SLC). The experiment involved the use of a Hoffman electrolysis apparatus. The following is the first section of the student's report.

What is the effect on current efficiency during electrolysis when the concentration of a sodium chloride, NaCl, solution is changed?

Aim

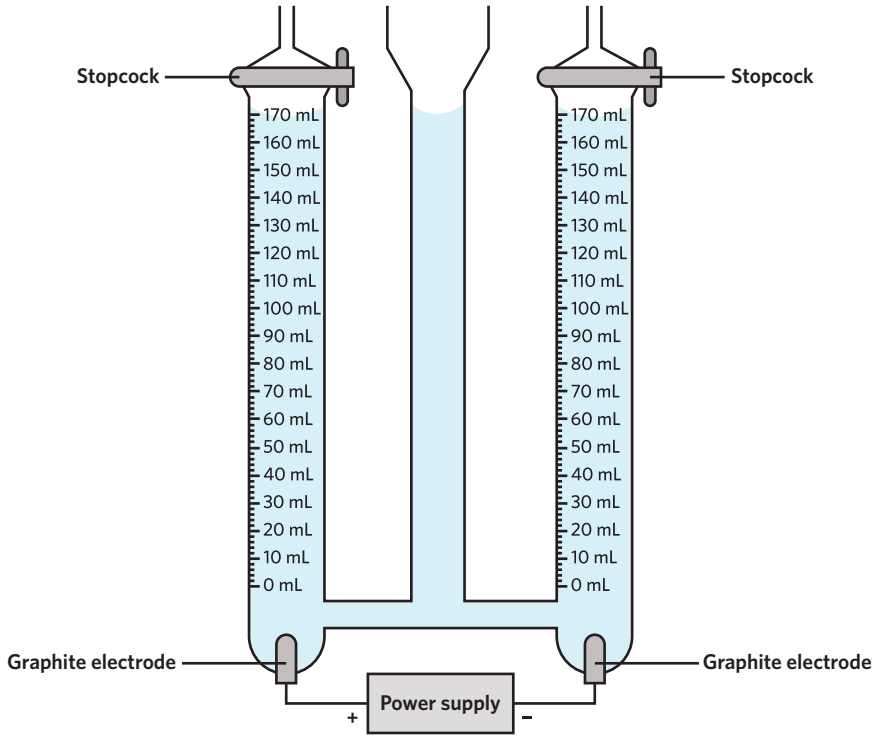
To investigate the effect on current efficiency during electrolysis when the concentration of a sodium chloride, NaCl, solution is changed

Procedure

1. Rinse the Hoffman electrolysis apparatus with distilled water.
2. Fill the Hoffman electrolysis apparatus with distilled water and add a small quantity of acid so that the bottom of the meniscus in both tubes is level with the 170 mL mark.
3. Connect the power supply and ammeter to the electrodes of the Hoffman electrolysis apparatus.
4. Turn on the power supply and start timing. Record the current displayed on the ammeter.
5. After 5.00 minutes, turn off the power supply and record the volume level on each of the tubes.
6. Repeat steps 2–5 four times.
7. Average the readings of the initial and final volumes at each electrode and current readings.
8. Repeat steps 1–7 using 1.5 M NaCl solution instead of distilled water and acid.
9. Repeat steps 1–7 using 4 M NaCl solution instead of distilled water and acid.

a. Identify the dependent variable. 1 MARK

b. A diagram of the Hoffman electrolysis apparatus, correctly filled as required in step 2, is shown.



The results for steps 1–7 of the procedure are given in Part 1.

Part 1 – Distilled water (with a small quantity of acid)

Trial	Initial volume (mL)		Final volume (mL)		Current (A)
	Negative electrode	Positive electrode	Negative electrode	Positive electrode	
1	170.0	170.0	100.2	135.3	2.0
2	170.0	170.0	100.3	135.3	2.0
3	170.0	170.0	99.9	135.0	2.0
4	170.0	170.0	99.8	134.8	2.0
5	170.0	170.0	100.1	135.1	2.0
Average	**170.0**	**170.0**	**100.1**	**135.1**	**2.0**

Are the results in Part 1 precise? Justify your answer. 1 MARK

c. Explain why a small quantity of acid is added to the distilled water in Part 1. 1 MARK

d. Write the half-equation for the reaction that would be expected to be observed at the negative electrode. 1 MARK

e. Consider the results given for Part 1 of the experiment.

i. Calculate the volume of gas (in mL) expected at the negative electrode for Part 1 of the experiment using Faraday's law. 3 MARKS

ii. Calculate the current efficiency for Part 1 of the experiment. 2 MARKS

f. The results for steps 8 and 9 of the procedure are given in Part 2 and Part 3.

Part 2 – 1.5 M NaCl (Step 8 of the procedure)

	Initial volume (mL)		Final volume (mL)		Current (A)
	Negative electrode	Positive electrode	Negative electrode	Positive electrode	
Average	170.0	170.0	98.0	133.2	2.0

Part 3 – 4 M NaCl (Step 9 of the procedure)

	Initial volume (mL)		Final volume (mL)		Current (A)
	Negative electrode	Positive electrode	Negative electrode	Positive electrode	
Average	170.0	170.0	95.2	100.0	2.0

What conclusion can be drawn from the results for parts 1, 2, and 3? 1 MARK

g. State the change the student should make to their experimental design to ensure they achieve their aim. Justify your answer. 2 MARKS

h. Scientists may use scientific posters to convey their research results to other scientists.

State two different aspects of the electrolysis experiment that the student should include in the discussion section of their scientific poster. 2 MARKS

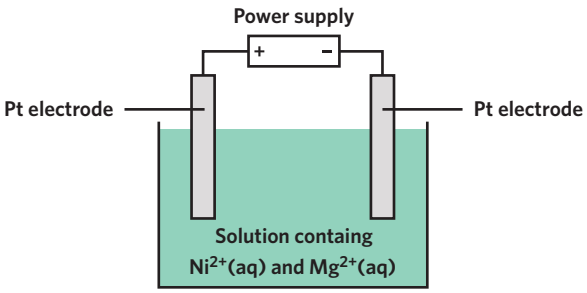
FROM LESSONS 12A, 12B, 12C, 12D & 12E

Adapted from VCAA 2019 exam Short answer Q9

Questions from multiple lessons

Question 14 (7 MARKS)

A mineral ore containing nickel and magnesium was extracted and treated with an acid. The solution obtained from the treatment was placed in an electrolytic cell as shown in the diagram.



a. Write balanced half-equations for the reaction occurring at

i. the anode. 1 MARK

ii. the cathode. 1 MARK

b. Given that 0.351 A was applied to the cell over 10 minutes, what mass of metal accumulated on the cathode? 3 MARKS

c. If the platinum cathode were replaced with lead, what effect would this have on the cell's function? Explain. 2 MARKS

FROM LESSONS 6A & 6B

Adapted from VCAA 2005 Exam 2 Short answer Q7

Question 15 (5 MARKS)

An unknown metal sulfate solution was electrolysed in a cell containing unreactive electrodes. After a total of 1.20 A was applied for 2.0 minutes, it was found that 7.46×10^{-4} mol of the metal A was produced.

a. Identify the charge, x, of the metallic ion (A^{x+}). 3 MARKS

b. Given that water was the strongest reducing agent present, the unknown metal ion was the strongest oxidising agent present, and a minimum voltage of +1.67 V was required to drive the reaction, identify the half-reaction occurring at the cathode. Assume the experiment was performed under standard laboratory conditions. 2 MARKS

FROM LESSON 6B

Chapter 6 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which one of the following is true of secondary cells?

A. Side reactions do not occur.

B. Fuel cells are a type of secondary cell.

C. The cathodes are always positively charged.

D. Electrical energy is transformed into chemical energy during the recharge cycle.

VCAA (NHT) 2023 exam Multiple choice Q2

Question 2 (1 MARK)

Which of the following is **not** true regarding the production of green hydrogen?

A. Green hydrogen is renewable.

B. Water is a product in the production of green hydrogen.

C. No greenhouse gases are produced in a PEM electrolyser.

D. Green hydrogen can be produced via artificial photosynthesis.

Question 3 (1 MARK)

When molten aluminium oxide, Al_2O_3, is electrolysed, the product formed at the cathode is

A. aluminium liquid, Al.

B. hydrogen gas, H_2.

C. water, H_2O.

D. oxygen gas, O_2.

Adapted from VCAA 2018 exam Multiple choice Q9

Use the following information to answer questions 4–5.

A copper disc is to be silver-plated in an electrolytic cell. The disc forms one electrode and a silver rod the other electrode. The electrolyte provides a source of $Ag^+(aq)$.

Question 4 (1 MARK)

The mass of silver to be deposited is 0.150 g. If the current is held steady at 1.50 A, the time, in seconds, that it takes to complete the plating is closest to

A. 90 **B.** 180 **C.** 200 **D.** 360

VCAA 2005 Exam 2 Multiple choice Q10

Question 5 (1 MARK)

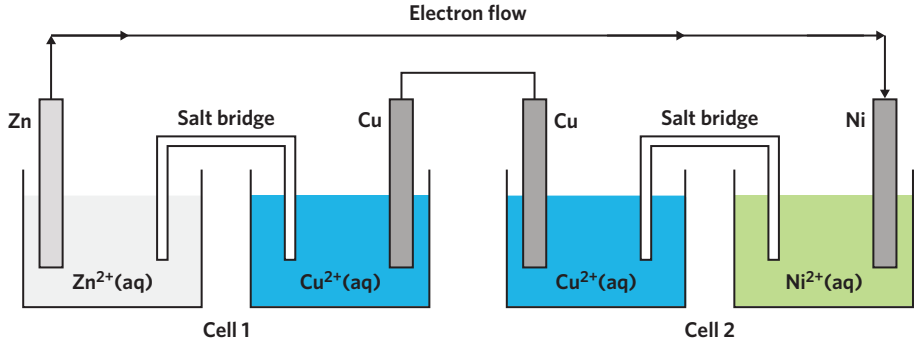
An identical disc is to be gold-plated with a solution containing $Au^{3+}(aq)$ as the electrolyte using a current of 1.50 A. The ratio of the time that is needed to plate the disc with 0.150 g of gold to the time needed to plate the disc with 0.150 g of silver is closest to

A. 1 to 3 **B.** 1 to 1.6 **C.** 1.6 to 1 **D.** 3 to 1

VCAA 2005 Exam 2 Multiple choice Q11

Question 6 (1 MARK)

The following diagram shows two connected electrochemical cells.



Which of the following gives the energy transformations that occur in Cell 1 and in Cell 2?

	Cell 1	Cell 2
A.	Chemical → electrical	Chemical → electrical
B.	Electrical → chemical	Chemical → electrical
C.	Chemical → electrical	Electrical → chemical
D.	Electrical → chemical	Electrical → chemical

VCAA 2021 exam Multiple choice Q29

Question 7 (1 MARK)

Fluorine can be produced commercially by the electrolysis of a mixture of potassium hydrogen difluoride, KHF_2, and hydrogen fluoride, HF. HF is a molecular gas at standard laboratory conditions (SLC).

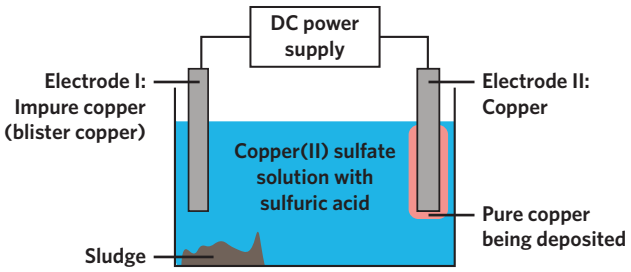
Which of the following pairs of statements about the electrolysis of HF to produce fluorine is correct?

	Molten HF is not used in electrolysis to produce fluorine because	Aqueous HF is not used in electrolysis to produce fluorine because
A.	HF is a molecule.	oxygen would be produced.
B.	HF is a molecule.	hydrogen would be produced.
C.	the melting temperature of HF is too high.	oxygen would be produced.
D.	the melting temperature of HF is too high.	hydrogen would be produced.

VCAA (NHT) 2022 exam Multiple choice Q29

Use the following information to answer questions 8–10.

An electrolytic cell is set up to obtain pure copper from an impure piece of copper called 'blister copper'. The electrolyte solution contains both copper(II) sulfate and sulfuric acid. The blister copper, Electrode I, contains impurities such as zinc, cobalt, silver, gold, nickel, and iron. The cell voltage is adjusted so that only copper is deposited on Electrode II. Sludge, which contains some of the solid metal impurities present in the blister copper, forms beneath Electrode I. The other impurities remain in solution as ions. The diagram shown represents the cell.



Question 8 (1 MARK)

The solid metal impurities that are found in the sludge are

A. gold, nickel, and cobalt.

B. cobalt, nickel, and iron.

C. nickel and iron.

D. silver and gold.

VCAA 2015 exam Multiple choice Q28

Question 9 (1 MARK)

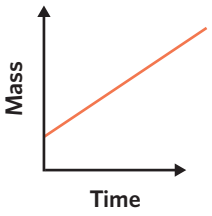
Which of the following correctly shows both the half-equation for the reaction occurring at the cathode and the polarity of Electrode I?

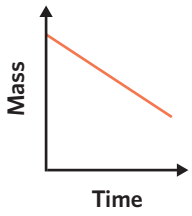
	Cathode reaction	Polarity of Electrode I
A.	$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	Positive
B.	$Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$	Negative
C.	$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	Negative
D.	$Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$	Positive

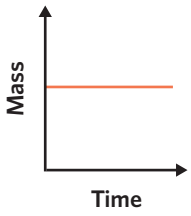
VCAA 2015 exam Multiple choice Q29

Question 10 (1 MARK)

Which one of the following graphs best shows the change in mass of Electrode I over a period of time, starting from the moment the power supply is connected?

A.


B.


C.


D.

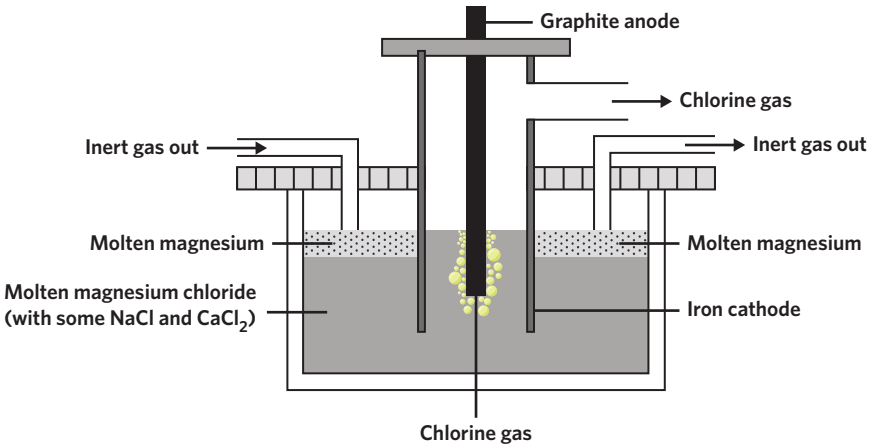

VCAA 2015 exam Multiple choice Q30

Short answer (30 MARKS)

Question 11 (8 MARKS)

Magnesium is one of the most abundant elements on Earth. It is used extensively in the production of magnesium-aluminium alloys. It is produced by the electrolysis of molten magnesium chloride.

A schematic diagram of the electrolytic cell is shown.



The design of this cell takes into account the following properties of both magnesium metal and magnesium chloride:

1. Molten magnesium reacts vigorously with oxygen.
2. At the temperature of molten magnesium chloride, magnesium is a liquid.
3. Molten magnesium has a lower density than molten magnesium chloride and forms a separate layer on the surface.

a. Write the balanced half-equation for the reaction occurring at each of

i. the cathode. 1 MARK

ii. the anode. 1 MARK

b. Explain why an inert gas is constantly blown through the cathode compartment. 1 MARK

c. The melting point of a compound can often be lowered by the addition of small amounts of other compounds. In an industrial process, this will save energy. In this cell, NaCl and $CaCl_2$ are used to lower the melting point of $MgCl_2$.

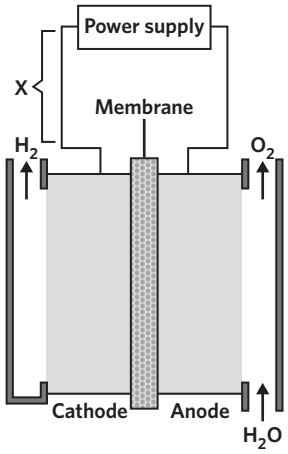
Why can NaCl and $CaCl_2$ be used to lower the melting point of $MgCl_2$, but $ZnCl_2$ cannot be used? 2 MARKS

d. What difference would it make to the half-cell reactions if the graphite anode were replaced with an iron anode? Write the half-equation for any different half-cell reaction. Justify your answer. 3 MARKS

VCAA 2014 exam Short answer Q9

Question 12 (10 MARKS)

Green hydrogen, H_2, can be produced using electricity generated by renewable sources. A simplified diagram of an acidic electrolyser used to produce hydrogen is shown.



a. Use an arrow to show the direction in which current flows through the segment of wire labelled X on the diagram. 1 MARK

b. State two functions of the membrane. 2 MARKS

c. Write the overall equation for the reaction that takes place in the acidic electrolyser shown in the diagram when it is operating at 80 °C. 1 MARKS

d. The cell was switched on for 1.25 hours, using a current of 1625.0 A.

i. How many moles of H_2 were produced, assuming 100% efficiency? 3 MARKS

ii. If the cell were operating at SLC, what volume of H_2 would have been produced? 1 MARK

e. Another method of producing green hydrogen is artificial photosynthesis. Is this process always carbon neutral? Explain. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q2

Question 13 (3 MARKS)

One source of Mg is magnesium chloride, $MgCl_2$, which can be obtained from seawater.

Explain how Mg can be produced from $MgCl_2$ in an electrolytic cell.

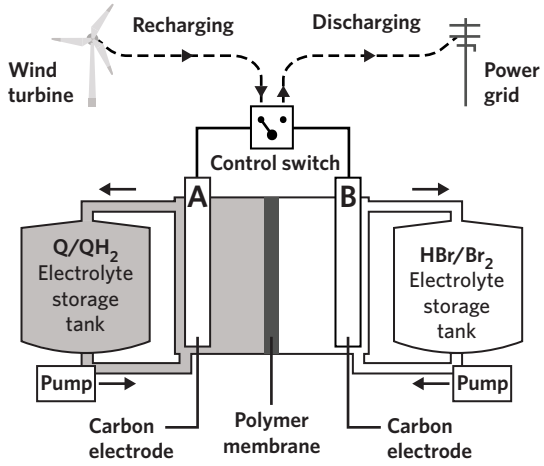
VCAA 2021 exam Short answer Q2c

Question 14 (9 MARKS)

Redox flow batteries are used to store the excess electrical energy generated by commercial wind and solar farms. The batteries are recharged using electricity generated by the wind turbines or solar cells. A scientific report, published in January 2014, described a redox flow battery that used a family of chemicals commonly occurring in plants such as rhubarb. These are organic and are known as quinones and hydroquinones. A diagram showing how such a redox flow battery might operate is provided.

In the diagram, Q represents the quinone, and QH_2 represents the corresponding hydroquinone.

The researchers made a model of the redox flow battery using aqueous solutions of the redox pairs Q/QH_2 and Br_2/Br^-.



During discharge, QH_2 is converted to Q, and Br_2 is converted to HBr.

a. Write balanced half equations for the reactions occurring at each electrode as the cell **discharges**. Assume the electrolytes are acidic.

i. Positive electrode 1 MARK

ii. Negative electrode 1 MARK

b. Write an overall equation for the reaction that occurs when the cell is **recharged**. Assume standard conditions. 1 MARK

c. The researchers reported that their tests indicated that only hydrogen ions were able to move through the polymer membrane separating the cells.

i. Use an arrow to indicate the direction of movement of H^+ ions through the polymer membrane during the recharge cycle. 1 MARK

ii. Why is it important that the other reactants in the half-cells are not able to pass through the polymer? 1 MARK

d. The researchers also reported that the voltage applied to the cell during recharging was kept below 1.5 V to avoid the electrolysis of water. Write an equation for the overall reaction that occurs when water is electrolysed. 1 MARK

e. Quinones have a number of industrial applications and are cheaply synthesised on a large scale from anthracene, which is found in crude oil. The report's researchers suggest that because these compounds also exist in plants such as rhubarb, the electrolyte material is itself a renewable resource. What is meant by the term 'renewable' in this context? 1 MARK

f. State one advantage of the choice of species in this cell in terms of the cell's ability to be recharged. Explain. 2 MARKS

Adapted from VCAA 2014 exam Short answer Q11

Key science skills (15 MARKS)

Question 15 (15 MARKS)

For an extended experimental investigation, a group of students designed and carried out experiments to investigate various aspects of electroplating. An extract from the scientific poster produced by one of these students is shown.

Introduction

Electroplating is generally carried out to improve the appearance or corrosion resistance of the surface of an object by depositing a thin layer of metal on it.

In this experiment, two copper electrodes were used in a solution of copper sulfate, $CuSO_4$.

Copper was plated onto the copper strip at the cathode.

The anode was connected to the positive terminal of the power supply.

Cathode half-reaction: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

Anode half-reaction: $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$

The copper strip was dipped in propanone, $(CH_3)_2CO$, before being weighed to determine the mass of copper plated on the electrode. Care needs to be taken when using $(CH_3)_2CO$.

$(CH_3)_2CO$ is harmful if inhaled and is highly flammable. Vapour may travel a considerable distance to the source of ignition.

The number of coulombs passed during the plating can be calculated by using the following formula.

$$Q = It$$

In this equation:

- Q is the charge, in coulombs.
- I is the average current, in amperes.
- t is the time, in seconds.

a. Considering the properties of $(CH_3)_2CO$ stated in the introduction, outline the safety precautions the student would take when

i. using $(CH_3)_2CO$. 1 MARK

ii. disposing of $(CH_3)_2CO$. 1 MARK

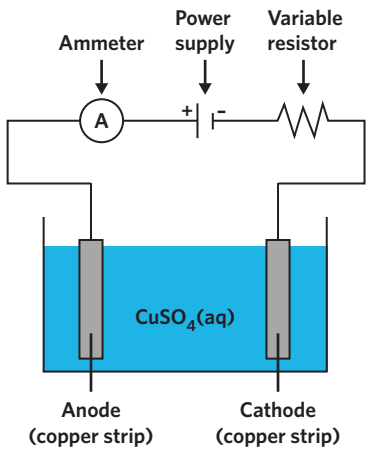
b. Another extract from the scientific poster is shown.

Aim

To find the amount of copper gained or lost on the electrodes using different amounts of current each time during electrolysis, and how changing the current affects the electroplating of copper.

Procedure

1. Cut identical strips of copper.
2. Clean the copper strips.
3. Weigh the copper strips.
4. Connect the copper strips to the electrodes.
5. Place them in the beaker of $CuSO_4$ solution.
6. Pass a current of 1.0 A through the cell for 10.0 minutes. Use 8.0 V.
7. Maintain the current by using a variable resistor.
8. Carefully remove the copper-plated electrode.
9. Dip this into the beaker of water.
10. Now dip it into the beaker of $(CH_3)_2CO$.
11. Allow it to dry and then weigh.
12. Repeat using different currents.



i. Name the independent variable in this experiment. 1 MARK

ii. Name a controlled variable in this experiment and state why it is important for this variable to be controlled. 2 MARKS

iii. The aim and the procedure stated by the student do not match.
Rewrite the aim so that it better matches the stated procedure. 2 MARKS

c. The student's results as presented on their poster are shown.

Results

Trial number	Current (A)	Mass of copper strip (g) before electroplating	Mass of copper strip (g) after electroplating	Mass of copper (g) plated
1	0.6	2.21	2.29	0.08
2	0.8	2.19	2.31	0.12
3	1.0	2.09	2.25	0.16
4	1.2	1.99	2.19	0.20
5	1.4	1.93	2.16	0.23

i. Suggest another way of displaying the results given in the table. 1 MARK

ii. Describe how the class data (data collected by other members of the class) could be used to determine the repeatability of the experiment. 2 MARKS

iii. Write a suitable conclusion for the results given in the table. 2 MARKS

d. As part of a peer assessment process, a group of students reviewed the investigation and suggested a number of changes. One of these suggested changes is as follows.

"Measure the mass of both the anode and cathode before and after electroplating."

Comment on how implementing this suggested change would affect the experiment with respect to:

- the validity of the experiment
- the sources of error (random and systematic). 3 MARKS

VCAA (NHT) 2018 exam Short answer Q8

FROM LESSONS 12A, 12B, 12C, 12D & 12E

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4

UNIT 4

How are carbon-based compounds designed for purpose?

Carbon is the basis not only of the structure of living tissues but is also found in fuels, foods, medicines, polymers and many other materials that we use in everyday life. In this unit students investigate the structures and reactions of carbon-based organic compounds, including considering how green chemistry principles are applied in the production of synthetic organic compounds. They study the metabolism of food and the action of medicines in the body. They explore how laboratory analysis and various instrumentation techniques can be applied to analyse organic compounds in order to identify them and to ensure product purity.

Students conduct practical investigations related to the synthesis and analysis of organic compounds, involving reaction pathways, organic synthesis, identification of functional groups, direct redox titrations, solvent extraction and distillations.

Throughout the unit students use chemistry terminology including symbols, formulas, chemical nomenclature and equations to represent and explain observations and data from their own investigations and to evaluate the chemistry-based claims of others.

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UNIT 4 AOS 1

How are organic compounds categorised and synthesised?

In this area of study students focus on the structure, naming, properties and reactions of organic compounds, including the chemical reactions associated with the metabolism of food. They explore how synthetic organic compounds can be produced more sustainably for use in society.

The selection of learning contexts should allow students to develop practical techniques to investigate organic structures and reactions. Students develop their skills in the use of scientific equipment and apparatus. They may construct models to explore organic structures, including isomers. Students may compare the properties of biodiesels produced using different oils, or may investigate organic reaction pathways such as the synthesis of esters used in food flavourings. They may investigate food metabolism by hydrolysing different types of plant starches. Students respond to challenges such as how to improve the atom economy of a selected chemical reaction or reaction pathway.

Outcome 1

On completion of this unit the student should be able to analyse the general structures and reactions of the major organic families of compounds, design reaction pathways for organic synthesis, and evaluate the sustainability of the manufacture of organic compounds used in society.

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7

CHAPTER 7

Structure, nomenclature and properties of organic compounds

LESSONS

7A Structures of organic compounds

7B Naming and properties of organic compounds

Chapter 7 review

KEY KNOWLEDGE

- characteristics of the carbon atom that contribute to the diversity of organic compounds formed, with reference to valence electron number, relative bond strength, relative stability of carbon bonds with other elements, degree of unsaturation, and the formation of structural isomers
- molecular, structural and semi-structural (condensed) formulas and skeletal structures of alkanes (including cyclohexane), alkenes, benzene, haloalkanes, primary amines, primary amides, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- the International Union of Pure and Applied Chemistry (IUPAC) systematic naming of organic compounds up to C8, with no more than two functional groups for a molecule, limited to non-cyclic hydrocarbons, haloalkanes, primary amines, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- trends in physical properties within or between homologous series (boiling point and melting point, viscosity), with reference to structure and bonding

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7A Structures of organic compounds

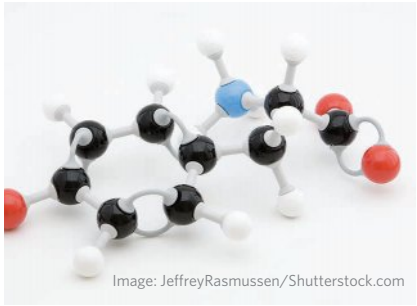


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Why are there so many types of organic compounds?

Carbon-based compounds are incredibly diverse and can have a wide range of properties, determined by their **functional groups**. In this lesson, we will explore the properties of the carbon atom, as well as different types and representations of **organic molecules**.

7A 7B

4.1.1.1 Carbon bonds (Pg 321)

4.1.2.1 Alkanes and alkenes (Pg 324)

4.1.2.2 Cyclohexane and benzene (Pg 325)

4.1.2.3 Haloalkanes (Pg 325)

4.1.2.4 Amines and amides (Pg 326)

4.1.2.5 Alcohols (Pg 327)

4.1.2.6 Aldehydes and ketones (Pg 328)

4.1.2.7 Carboxylic acids (Pg 329)

4.1.2.8 Esters (Pg 329)

ESSENTIAL PRIOR KNOWLEDGE

- Covalent bonding
- Electronegativity
- Polarity

See questions 60–62.

STUDY DESIGN DOT POINTS

- characteristics of the carbon atom that contribute to the diversity of organic compounds formed, with reference to valence electron number, relative bond strength, relative stability of carbon bonds with other elements, degree of unsaturation, and the formation of structural isomers
- molecular, structural and semi-structural (condensed) formulas and skeletal structures of alkanes (including cyclohexane), alkenes, benzene, haloalkanes, primary amines, primary amides, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters

KEY TERMS AND DEFINITIONS

Aldehyde organic compound that contains an aldehyde functional group (−CHO)

Alkene hydrocarbon that includes at least one carbon-carbon double bond functional group (C=C)

Alkyl group group containing only carbon and hydrogen atoms (e.g. $-CH_3$, $-CH_2CH_3$)

Amine organic compound with an amino functional group ($-NH_2$)

Carboxyl group a combination of two functional groups (−COOH) attached to a single carbon atom, namely, hydroxyl (−OH) and carbonyl (C=O) groups

Degree of unsaturation a measure of the number of double and triple bonds in a compound

Electronegativity how strongly an atom attracts electrons towards itself

Empirical formula chemical formula showing the lowest whole number ratio of the number of atoms in a compound

Ester organic compound that contains an ester functional group (−COOC−)

Functional group specific group of atoms within a compound that affects the chemical properties of the compound

Haloalkane organic compound that has one or more halogen atom (element in group 7 of the periodic table, often represented by 'X')

Hydroxyl a functional group (−OH) with one hydrogen and one oxygen atom

Ketone organic compound that contains a carbonyl functional group (C=O), where the carbon atom in the −C=O group is bonded to two other carbon atoms

Molecular formula chemical formula that shows the number of each atom in a molecule

Molecule two or more atoms covalently bonded by sharing electrons

Organic containing carbon

Primary amide organic compound that contains an amide functional group at a terminal carbon atom ($-CONH_2$)

Saturated (organic compound) possessing only single bonds between carbon atoms

Semi-structural (condensed) formula condensed form of a structural formula that does not show all bonds between atoms in a compound

Skeletal formula representation of a molecular structure where covalent bonds are shown as lines, carbon atoms are shown as vertices, and hydrogen atoms bonded to carbon atoms are not shown

Structural formula representation of a molecule that shows all the atoms and bonds in an atom or compound

Terminal carbon carbon atom at the end of the carbon parent chain

Unsaturated (organic compound) possessing at least one double or triple bond between carbon atoms

Valence electron number number of electrons in the outer (valence) shell of an atom

Carbon bonds 4.1.1.1

Carbon bonding is the foundation of all organic compounds.

Why are carbon compounds so diverse?

Organic compounds are identified as those where carbon is covalently bonded to other atoms. Most often this involves other carbon atoms, hydrogen, nitrogen, and oxygen.

MISCONCEPTION

'In chemistry, 'organic' means naturally occuring.'

Although the term organic is often used to describe things as natural, such as 'organic' food, this is not what the term means in chemistry. When a molecule is described as an organic molecule, this means that the molecule is carbon-based, and may be either naturally or synthetically produced.

The ability of carbon to form a diverse range of compounds by bonding to a variety of different atoms is due to a combination of factors, including:

- its **valence electron number**
- relative bond strength
- relative stability of carbon bonds with other elements.

KEEN TO INVESTIGATE?

1 **What do covalent bonds actually look like?**
Search YouTube: Scientists capture actual images of chemical bonds

Valence electron number

Carbon atoms have a valence electron number of four, meaning each carbon atom forms four bonds in a tetrahedral arrangement (figure 1).[1] These four valence electrons also mean that carbon is able to form either single, double, or triple bonds with either itself or other elements (figure 2). For this reason, carbon-containing compounds can either be **saturated** (containing only single carbon-to-carbon bonds) or **unsaturated** (containing at least one double or triple carbon-to-carbon bond).

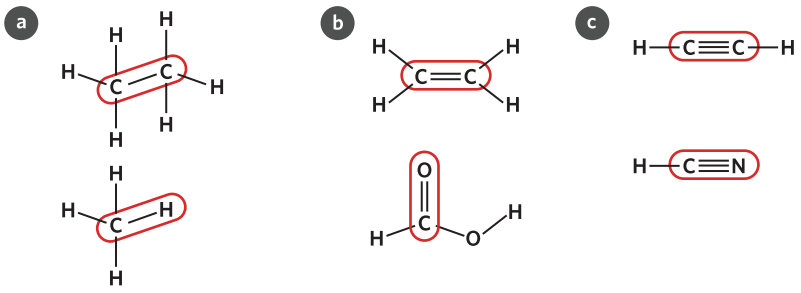


Figure 2 Carbon atoms can form **(a)** single, **(b)** double, and **(c)** triple bonds with themselves and other elements.

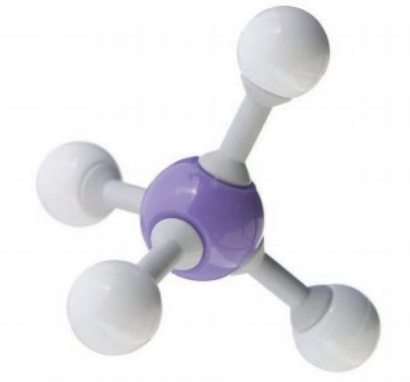


Image: JeffreyRasmussen/Shutterstock.com

Figure 1 Model of tetrahedral bonding of a carbon atom to four hydrogen atoms

Relative bond strength and stability of carbon bonds with other elements

The bond strength of a particular carbon bond depends on the bond energy (energy required to break the chemical bond). There are various factors that impact the energy of a chemical bond, including:

- bond length
- the difference in **electronegativity** of the atoms involved
- size of the atoms.

The distance between the nuclei of two bonded atoms is known as the bond length (figure 3). The length of the bond will vary depending on the strength of the electrostatic attraction between the nuclei of the bonded atoms and their shared electrons. The size of the atoms involved also impacts the bond length; bonds between larger atoms are expected to be longer.

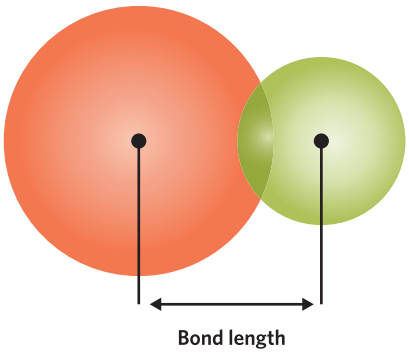


Figure 3 How bond length is measured

In general, bond energy (and hence bond strength) increases as the length of a bond decreases. Table 1 compares the bond length and bond energy of common chemical bonds.

Table 1 Bond energies and lengths of common bonds

Bond	Energy in kJ mol^{-1}	Length in pm (10^{-12} m)
Single bonds		
H—H	432	74
H—F	565	92
H—Cl	427	127
H—Br	363	141
H—I	295	161
C—H	413	109
C—C	347	154
C—Si	301	186
C—N	305	147
C—O	358	143
C—P	264	187
C—S	259	181
C—F	453	133
C—Cl	339	177
C—Br	276	194
C—I	216	213
Multiple bonds		
C=C	614	134
C=N	615	127
C=O	745 (779 in CO_2)	123

From table 1, a relationship between bond energy and electronegativity can also be determined. That is, bonds formed between elements with larger differences in electronegativity form stronger bonds. You may recall that electronegativity increases across the period of the periodic table from left to right, and up the groups of the periodic table (figure 4).

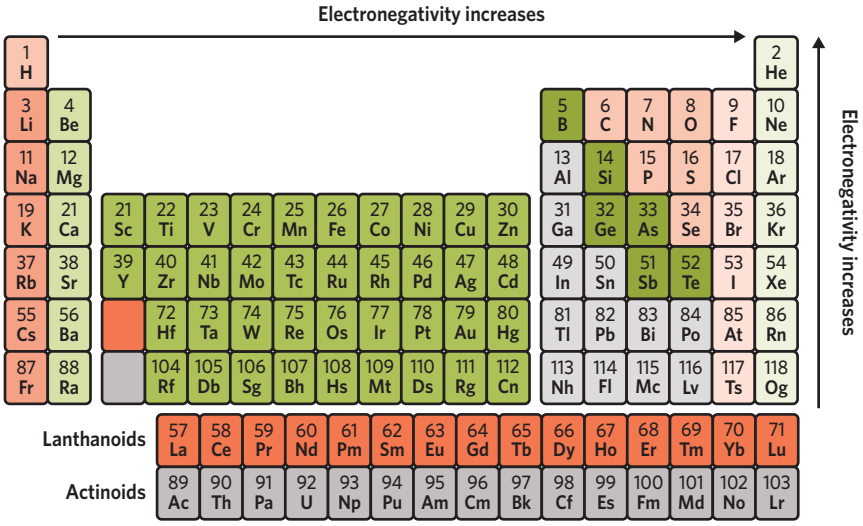


Figure 4 Electronegativity trends in the periodic table

PROGRESS QUESTIONS

Question 1

Which of the following factors affect(s) bond strength?

I. Bond length

II. Atomic number

III. Electronegativity

A. I only **B.** I and II only **C.** II and III only **D.** I and III only

Question 2

Which of the following statements is **incorrect** about carbon atoms?

A. They typically form stable compounds.

B. They typically form weak chemical bonds.

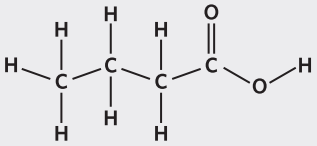
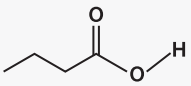
C. They can be involved in four covalent bonds.

D. Carbon-carbon bonds contain a relatively large amount of chemical energy.

How can we represent organic compounds?

There are a variety of ways to represent organic compounds. These are outlined in table 2.

Table 2 Different types of formulas and their representations for butanoic acid

Formula	Representation	What it shows
Structural formula		• All atoms and bonds within a compound
Skeletal formula		• Most atoms and bonds within a compound • Covalent bonds are shown as lines, and carbon atoms are shown as vertices. • Hydrogen atoms bonded to carbon atoms are not shown.
Semi-structural (condensed) formula	$CH_3CH_2CH_2COOH$ or $CH_3(CH_2)_2COOH$	• All atoms and their location • Often double and triple carbon-carbon bonds are included (e.g. $H_2C{=}CH_2$). • Repeating units (e.g. CH_2) are often placed in brackets, and the number of repeating units is written outside the brackets (e.g. $(CH_2)_2$).
Molecular formula	$C_4H_8O_2$	• The number of each type of atom in a compound
Empirical formula	C_2H_4O	• The lowest whole number ratio of the number of atoms in a compound (can be multiplied by a whole number to determine the molecular formula) • May be the same as the molecular formula if the molecular formula cannot be simplified (subscripts do not share a common factor)

PROGRESS QUESTIONS

Question 3

What type of chemical formula used in VCE chemistry provides the most information about a compound?

A. Empirical formula

B. Molecular formula

C. Structural formula

D. Semi-structural formula

Alkanes and alkenes 4.1.2.1

Alkanes and **alkenes** are hydrocarbons with different carbon bonding structures, and they form many naturally occurring carbon-based fuels.

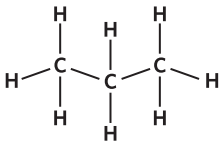
What are alkanes and alkenes?

Alkanes

As we learned in Unit 1, alkanes are saturated hydrocarbons that have only single carbon-carbon bonds in their structures. The general formula of alkanes is C_nH_{2n+2}, where n represents the number of carbon atoms in the structure.

As shown in figure 5, alkanes are usually arranged as either linear or branched chains (due to the presence of side chains).

Linear chain arrangement



Branched arrangement

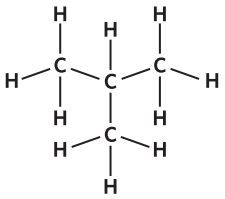


Figure 5 Common structural arrangements of alkanes

USEFUL TIP

Carbon-carbon bonds are always non-polar. (Charge is dispersed evenly between these bonds.)

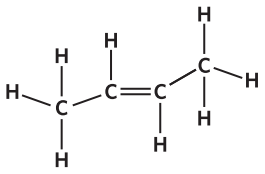


Figure 6 Structural formula of but-2-ene (an alkene)

Alkenes

Alkenes are unsaturated hydrocarbons that have at least one carbon-carbon double bond in their carbon chain, meaning they have at least one **degree of unsaturation**. Methods for identifying and measuring degree of unsaturation are explored in lessons 9A and 9C.

The general formula of alkenes is C_nH_{2n}. Although we often see and draw alkenes as linear structures, in reality, the double bond causes a 'kink' in the carbon chain, as shown in figure 6. Like alkanes, alkenes can form either branched or linear structures.

PROGRESS QUESTIONS

Question 4

Which of the following structural formulas may represent an alkene?

A. C_4H_{10}

B. C_8H_{18}

C. C_3H_6

D. $C_{12}H_{26}$

Cyclohexane and benzene 4.1.2.2

Cyclohexane and benzene are hydrocarbons with a cyclic structure.

What are cyclohexane and benzene?

Cyclohexane

Cyclohexane (figure 7) is an example of a cycloalkane: an alkane arranged in a closed ring with no **terminal carbon**. In this structure, each carbon atom is bonded to two adjacent carbon atoms and two hydrogen atoms. Unlike straight-chain alkanes and branched alkanes, cycloalkanes have the general formula C_nH_{2n}.

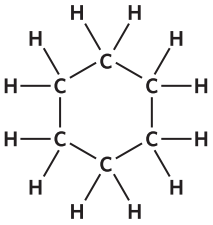


Figure 7 Structure of cyclohexane

Benzene

Benzene is a cyclic compound that has 6 carbon atoms in its ring structure, each bonded to one hydrogen atom and two adjacent carbon atoms. One electron from each carbon atom is delocalised and shared equally between carbon atoms in the ring, resulting in a very stable formation. This is sometimes represented by a circle; a number of equivalent representations of benzene are shown in figure 8. Benzene is a type of aromatic ring, which will be covered in lesson 11A.

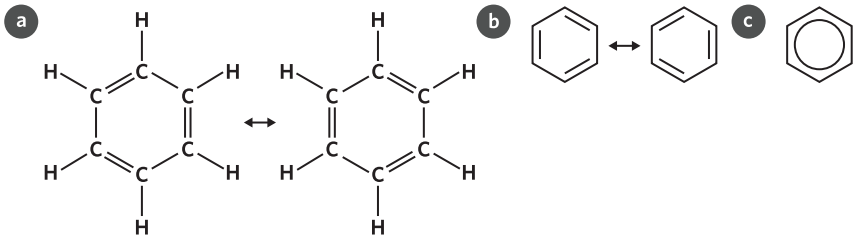


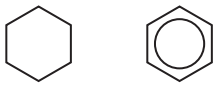
Figure 8 Three structural representations of benzene: **(a)** structural, **(b)** skeletal, and **(c)** ring

PROGRESS QUESTIONS

Question 5

Consider the skeletal formulas for cyclohexane and benzene.

Cyclohexane **Benzene**



How many hydrogen atoms are present in cyclohexane and benzene, respectively?

A. 12 and 12 **B.** 6 and 6 **C.** 12 and 9 **D.** 12 and 6

Haloalkanes 4.1.2.3

Haloalkanes are alkane-based compounds that have one or more halogen atoms bonded to the carbon chain.

What are haloalkanes?

A haloalkane (figure 9) is formed by replacing one or more hydrogen atoms attached to an alkane's carbon chain with a halogen (an atom found in group 17 of the periodic table). Halogens include chlorine, bromine, fluorine, and iodine; 'X' is often used as a general representation of a halogen (figure 10). As halogens are more electronegative than carbon atoms, they have a greater tendency to attract the shared pair of electrons to their own nucleus. This results in a polar bond: the carbon atom has a partial positive charge, whilst the halogen atom has a partial negative charge, as shown in figure 10.

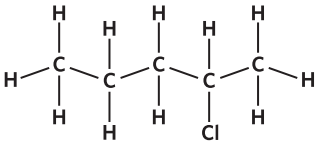


Figure 9 Structural formula of 2-chloropentane (a haloalkane)

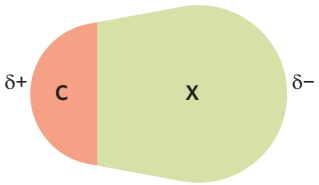


Figure 10 Electron distribution and partial charges across the polar bond between a carbon and a halogen

PROGRESS QUESTIONS

Question 6

Which statement is **incorrect** about the structure of haloalkanes?

A. Haloalkanes are formed by replacing one or more hydrogen atoms in the carbon chain of alkanes with halogen atoms (Cl, Br, I, F, ...).

B. The carbon-halogen bond in a haloalkane is polar.

C. The position and number of halogen atoms are the same for each haloalkane compound.

D. The three types of haloalkanes are linear straight-chain haloalkanes, branched haloalkanes, and cyclohaloalkanes.

Amines and amides 4.1.2.4

Amines and amides are compounds whose functional group contains a carbon-nitrogen bond. These compounds have numerous uses in medicinal chemistry, which will be discussed further in lesson 11B.

What are amines and amides?

Amines

Amines are named as such because they are generally derived from ammonia. As shown in figure 11, a hydrogen atom may be removed from ammonia (NH_3) to form an amino (or amine) functional group ($-NH_2$). As nitrogen can form three bonds with other atoms, the nitrogen atom in the amino group is free to bond to an **alkyl group** to form an amine (figure 12).

USEFUL TIP

R is an abbreviation that is used in organic chemistry for any group in which a carbon or hydrogen atom is attached to the rest of the molecule. This helps simplify what is occurring in reactions.

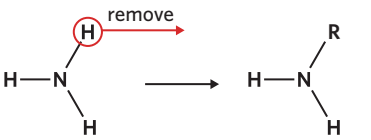


Figure 11 The formation of an amino group from ammonia

USEFUL TIP

N–H bonds are highly polar (negative charge shifts towards N).

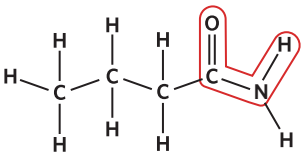


Figure 13 The structural formula of butanamide (a primary amide).

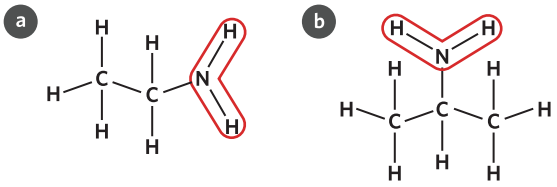


Figure 12 Structural formula of primary amines **(a)** ethanamine and **(b)** propan-2-amine

Primary amides

Amide functional groups ($-CONH$) differ from amine functional groups ($-NH_2$), in that they contain a carbonyl group (C=O) whose carbon atom is bonded to a nitrogen atom.Amides (figure 13) are organic compounds that contain an amide group.

Primary amides are amides in which the nitrogen atom is only bonded to one carbon atom. This means that in primary amides, the amide group will only be found at a terminal carbon (figure 13).

PROGRESS QUESTIONS

Question 7

Which statement is true about the structure of primary amides?

A. The oxygen atom in the amide functional group is directly bonded to the carbon atom.

B. The oxygen atom in the amide functional group is directly bonded to the hydrogen atom.

C. The functional group of a primary amide is CO.

D. The nitrogen atom in the primary amide functional group is linked to three alkyl groups.

Continues →

Question 8

Consider an organic compound with molecular formula $C_5H_{13}N$.
Is this compound a primary amine?

A. No. It does not contain an amine ($-NH_2$) group.

B. Yes. It contains an amine ($-NH_2$) functional group.

C. Yes. The nitrogen atom is bonded to a terminal carbon.

D. This cannot be determined from the information provided.

Alcohols 4.1.2.5

Alcohols are derivatives of hydrocarbons that have a **hydroxyl** ($-OH$) group bonded to a carbon atom in the carbon chain. There are three types of alcohols: primary alcohols, secondary alcohols, and tertiary alcohols.

What are alcohols?

Alcohols are formed when hydrocarbons have one or more of their hydrogen atoms replaced by a hydroxyl ($-OH$) group. Figure 14 shows the three types of alcohols that can form.

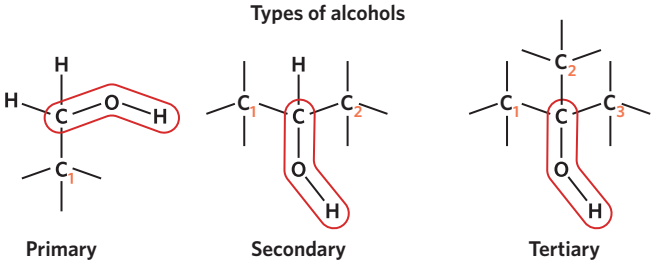


Figure 14 Types of alcohols

As shown in figure 14, the categorisation of an alcohol depends on the number of alkyl groups bonded to the carbon atom that the hydroxyl group is bonded to. In a primary alcohol, the carbon atom bonded to the hydroxyl group is bonded to only one alkyl group. The carbon atom bonded to the hydroxyl group in a secondary and tertiary alcohol is bonded to two and three alkyl groups respectively. Figure 15 shows the structure of a primary alcohol.

USEFUL TIP

Tertiary alcohols are very stable structures and consequently are unreactive.

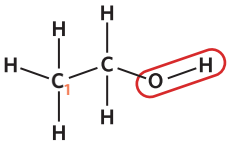


Figure 15 Structural formula of ethanol (a primary alcohol)

USEFUL TIP

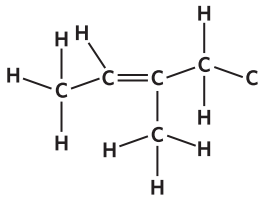
O–H bonds are highly polar (negative charge shifts towards O).

PROGRESS QUESTIONS

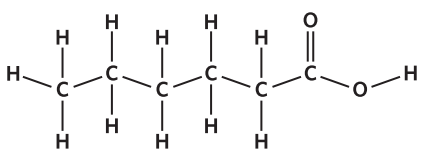
Question 9

Which of the structural formulas shown represents a primary alcohol?

A.

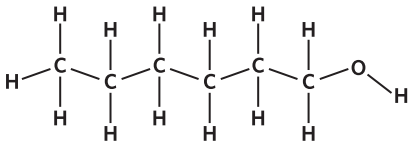


B.

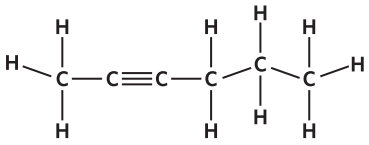


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C.



D.



Aldehydes and ketones 4.1.2.6

Aldehydes and **ketones** are compounds that have a carbonyl group (C=O) in their structures.

What are aldehydes and ketones?

Both aldehydes and ketones contain a carbon-oxygen double bond. As shown in figure 16, the carbon in the carbonyl group is able to take part in two more covalent bonds.



Figure 16 Carbonyl functional group

USEFUL TIP

C=O bonds are polar. (Negative charge shifts towards O.)

Aldehydes

In aldehydes (figure 17), one of the remaining bonds on the carbon atom in the carbonyl group is bonded to a hydrogen atom, forming the aldehyde functional group (−CHO), which can only exist at the end of a carbon chain. The carbon atom can then either bond with a hydrogen atom or an alkyl group.

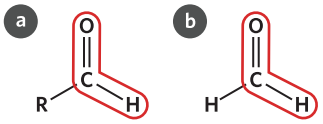


Figure 17 The structure of **(a)** the aldehyde functional group, where R represents an alkyl group, and **(b)** the structural formula for methanal (an aldehyde)

Ketones

In ketones, each of the two remaining bonds on the carbon in the carbonyl group are bonded to an alkyl group. As shown in figure 18, the two alkyl groups bonded to the carbon in the CO group do not have to be the same. Whilst aldehyde groups only exist at the end of a carbon chain, ketone functional groups can only exist within the carbon chain.

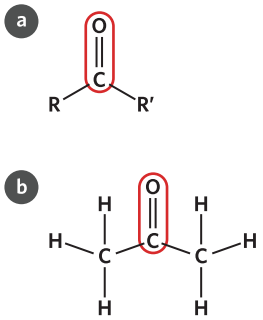


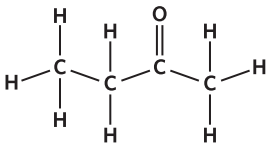
Figure 18 Structure of **(a)** a ketone functional group, where R and R′ represent two different alkyl groups, and **(b)** propanone (a ketone)

PROGRESS QUESTIONS

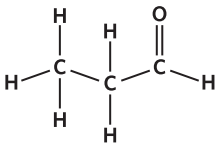
Question 10

Which statement is true about the structures shown?

I



II



A. Both compounds are aldehydes.

B. Both compounds are ketones.

C. Structure (I) is a ketone, and structure (II) is an aldehyde.

D. Structure (II) is a ketone, and structure (I) is an aldehyde.

Carboxylic acids 4.1.2.7

Carboxylic acids are another type of organic compound that contains a functional group made up of two other functional groups: a hydroxyl (−OH) and carbonyl (C=O).

What are carboxylic acids?

Carboxylic acids contain a **carboxyl** group (−COOH), which is always found at the end of the carbon chain. As the carboxyl group has the capacity to donate its H^+ into a solution, it is able to act as a weak acid. The carboxyl group may either bond to an alkyl group or a hydrogen atom (figure 19).

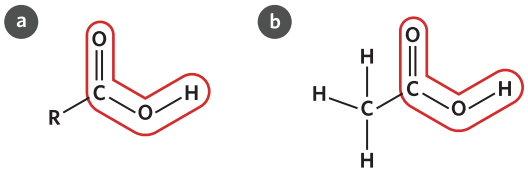


Figure 19 Structure of **(a)** a carboxyl functional group, where R represents an alkyl group, and **(b)** ethanoic acid (a carboxylic acid)

PROGRESS QUESTIONS

Question 11

Which of the following semi-structural formulas represents a carboxylic acid?

A. $CH_3CH_2CH_2CH_2CH_2COOH$

B. $CH_3CH_2CH_2CH_2CH_2COH$

C. $CH_3CH_2COOCH_2CH_3$

D. $CH_3CH_2COCH_2CH_3$

Esters 4.1.2.8

Similar to alcohols, aldehydes, ketones, and carboxylic acids, esters contain a functional group involving oxygen atoms. Esters are often used in perfumes and synthetic flavouring for their distinctive fragrances.

What are non-branched esters?

The distinguishing structural feature of an ester is that it has an ester (−COOC−) group, which is found within the carbon chain. As shown in figure 20, one carbon atom in the ester group is linked to one oxygen atom through a double bond (a carbonyl) and to another oxygen atom through a single bond. The oxygen atom in the single carbon-oxygen bond is then itself bonded to an alkyl group. Figure 21 shows some commonly used esters.

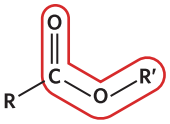


Figure 20 Structure of an ester functional group, where R represents either an alkyl group or an H atom, and R′ represents an alkyl group

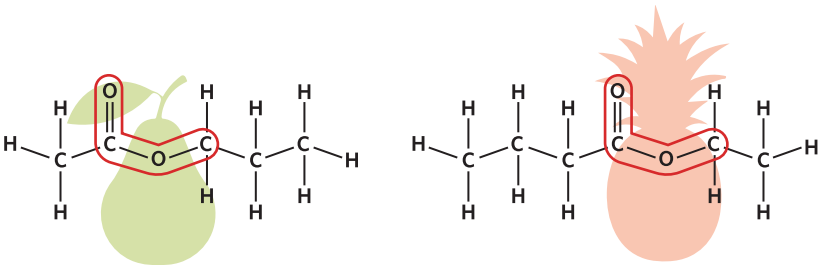


Figure 21 Structural formula of propyl ethanoate and ethyl butanoate, esters responsible for pear and pineapple smells respectively.

MISCONCEPTION

'An ester bond only contains a −COO− group.'

Esters contain a −COOC− functional group. If the carbon at the end is not included (−COO−), it may also refer to other groups, such as a COOH group.

WORKED EXAMPLE 1

Which of the following semi-structural formulas would represent an ester?
Assume that the molecule contains only one functional group.

A. $HOOC(CH_2)_5CH_3$
B. $CH_3CH_2COOCH_3$
C. $CH_3(CH_2)_4COCH_2CH_3$
D. $CH_3(CH_2)_7CH(CH_3)CH_3$

What information is presented in the question?

The correct option must contain an ester functional group.

What is the question asking us to do?

Identify the semi-structural formula that represents an ester.

What strategies do we need in order to answer the question?

1. Recall that an ester contains a (−COOC−) functional group.

Answer

An ester functional group (−COOC−) contains two oxygen atoms. Therefore, options C (1 oxygen atom) and D (0 oxygen atoms) are incorrect.

Option A is incorrect, as it contains only a carboxylic acid (−COOH) functional group.

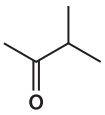
Option B contains an ester (−COOC−) group.
Therefore, option B represents an ester and is correct.

PROGRESS QUESTIONS

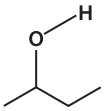
Question 12

Which one of the following skeletal formulas represents an ester?

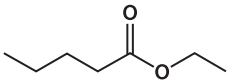
A.



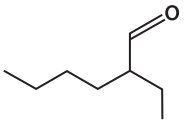
B.



C.

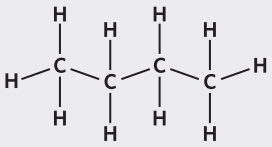
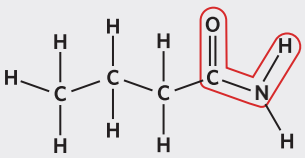
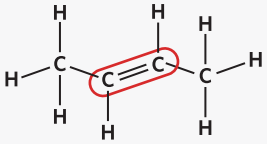
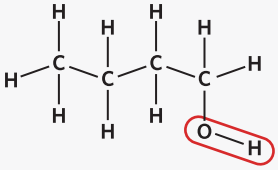
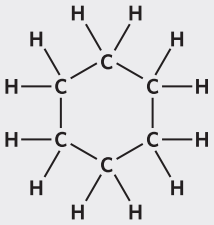
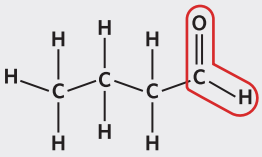
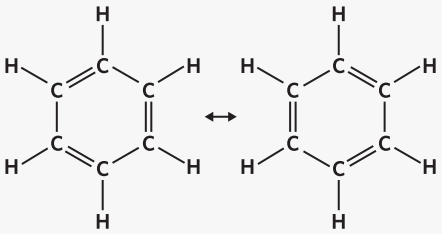
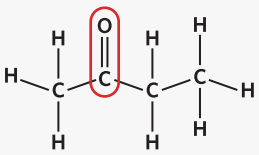
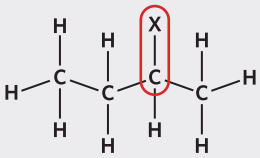
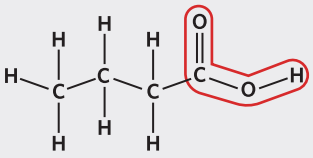
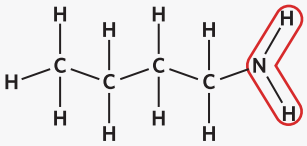
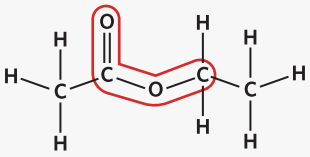


D.



Theory summary

- Carbon-based (organic) compounds are diverse due to the carbon atom's:
  - four valence electrons (tetravalent)
  - ability to form strong and stable single, double, or triple bonds with itself and other elements.
- Organic compounds can be represented by their:
  - structural formula (shows all atoms and bonds)
  - skeletal formula (shows most atoms and bonds)
  - semi-structural (condensed) formula (shows all atoms and their location)
  - molecular formula (shows the number of each type of atom)
  - empirical formula (shows the simplest ratio of the numbers of each type of atom).

Type of organic compound	Functional group (circled in red)	Type of organic compound	Functional group (circled in red)
Alkane		**Primary amide**	 Amide group
Alkene		**Alcohol**	 Hydroxyl group
Cycloalkane (includes cyclohexane)		**Aldehyde**	 Aldehyde group
Benzene		**Ketone**	 Carbonyl group
Haloalkane	 Halogen group X represents a halogen (group 17 of the periodic table).	**Carboxylic acid**	 Carboxyl group
Primary amine	 Amino group	**Ester**	 Ester group

- There are three types of alcohols:
  - Primary alcohol: hydroxyl group is bonded to a carbon atom that is bonded to only one alkyl group.
  - Secondary alcohol: hydroxyl group is bonded to a carbon atom that is bonded to two alkyl groups.
  - Tertiary alcohol (highly unreactive): hydroxyl group is bonded to a carbon atom that is bonded to three alkyl groups.

7A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 13–15.

A compound with the formula $C_6H_{12}O_2$ has the following features:

- It is unbranched.
- It only has one type of functional group.
- All carbon-to-carbon bonds are single bonds.

Question 13 (1 MARK)

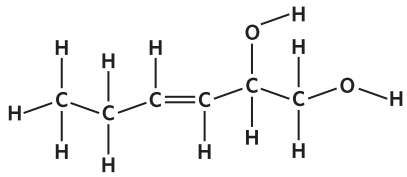
Which of the following functional groups contains a nitrogen atom?

A. Ester **B.** Amide **C.** Alcohol **D.** Aldehyde

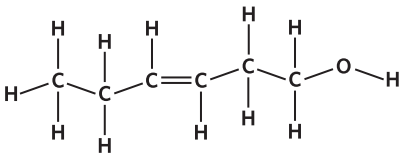
Question 14 (1 MARK)

Which of the following structural formulas represents an organic compound that contains two hydroxyl groups and had a molecular formula $C_6H_{12}O_2$?

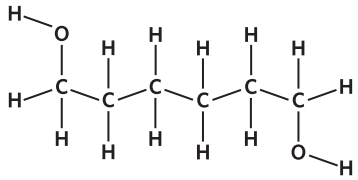
A.



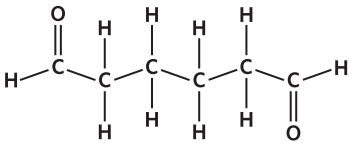
B.



C.



D.



Question 15 (1 MARK)

The compound, $C_6H_{12}O_2$, could be classified as an

A. ester.

B. amide.

C. alcohol.

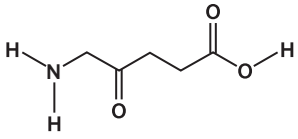
D. aldehyde.

VCAA (NHT) 2019 exam Multiple choice Q18

Exam-style

Question 16 (1 MARK)

How many different functional groups can be found in the molecule shown?



A. 4

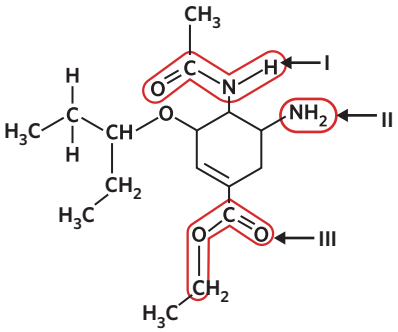
B. 3

C. 2

D. 1

Question 17 (3 MARKS)

The structure of Tamiflu®, an antiflu drug, is shown.



a. What is the functional group labelled I? 1 MARK

b. What is the functional group labelled II? 1 MARK

c. What is the functional group labelled III? 1 MARK

Adapted from VCAA 2010 Exam 1 Multiple choice Q19

Question 18 (2 MARKS)

Aldehydes and ketones can have the same molecular formula, but different structural formulas and functional groups. From the molecular formula C_3H_6O, draw the structural formula of

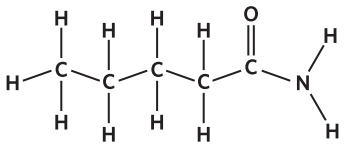
a. an aldehyde. 1 MARK

b. a ketone. 1 MARK

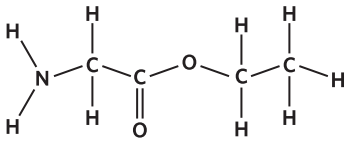
Question 19 (4 MARKS)

For the molecules shown,

a. circle and identify the functional group(s) present. 2 MARKS

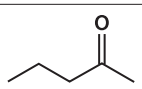
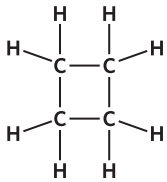
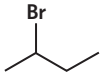


b. circle and identify the functional group(s) present. 2 MARKS



Question 20 (6 MARKS)

Draw the correct semi-structural, structural, and skeletal formulas that would complete the table shown.

Semi-structural formula	Structural formula	Skeletal formula
$CH_3CHC(CH_3)CH_3$		
$CH_3CH_2CH_2COCH_3$		
$CH_2CH_2CH_2CH_2$		
		

Question 21 (3 MARKS)

Consider an organic molecule with molecular formula C_4H_9OH. For this molecular formula:

a. Draw a primary alcohol. 1 MARK

b. Draw a secondary alcohol. 1 MARK

c. Draw a tertiary alcohol. 1 MARK

Question 22 (2 MARKS)

Carbon is able to bond to many different elements. The length of a carbon-nitrogen bond is 147 pm (147×10^{-12} m), whereas the length of a carbon-hydrogen bond is only 109 pm (109×10^{-12} m). Which of the two bonds would be predicted to have a higher bond energy? Explain.

Key science skills

Question 23 (2 MARKS)

Through a series of tests, a scientist determined that an unbranched organic compound with molecular formula $C_{22}H_{46}$ was present in a sample of seawater after an oil spill.

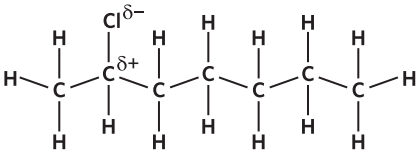
a. Is this an example of qualitative or quantitative data? 1 MARK

b. Write the semi-structural (condensed) formula for the compound with this molecular formula. 1 MARK

FROM LESSON 12B

Question 24 (1 MARK)

Consider the following structural formula and semi-structural (condensed) formula that represent the same organic compound.



$CH_3CHCl(CH_2)_4CH_3$

What is the structural formula able to convey that the semi-structural formula does not?

FROM LESSON 12E

Question 25 (1 MARK)

Why may a scientist use a skeletal formula to represent a complex organic compound instead of its structural formula?

FROM LESSON 12E

Questions from multiple lessons

Question 26 (6 MARKS)

Biobutanol, produced through the fermentation of biomass, can be blended with petrol and used as a car fuel. The semi-structural formula of biobutanol is shown.

$CH_3CH_2CH_2CH_2OH$

a. Identify whether this biobutanol is a renewable or non-renewable resource. 1 MARK

b. Identify the type of alcohol that biobutanol would be classified as. Explain. 2 MARKS

c. Biobutanol undergoes combustion as shown.

$C_4H_9OH(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$

Given that the heat of combustion of butanol is 2676 kJ mol^{-1}, determine the mass of oxygen that would be used up if 1033 kJ of energy was released during the reaction. 3 MARKS

FROM LESSONS 1B & 2A

Back to contents

7B Naming and properties of organic compounds

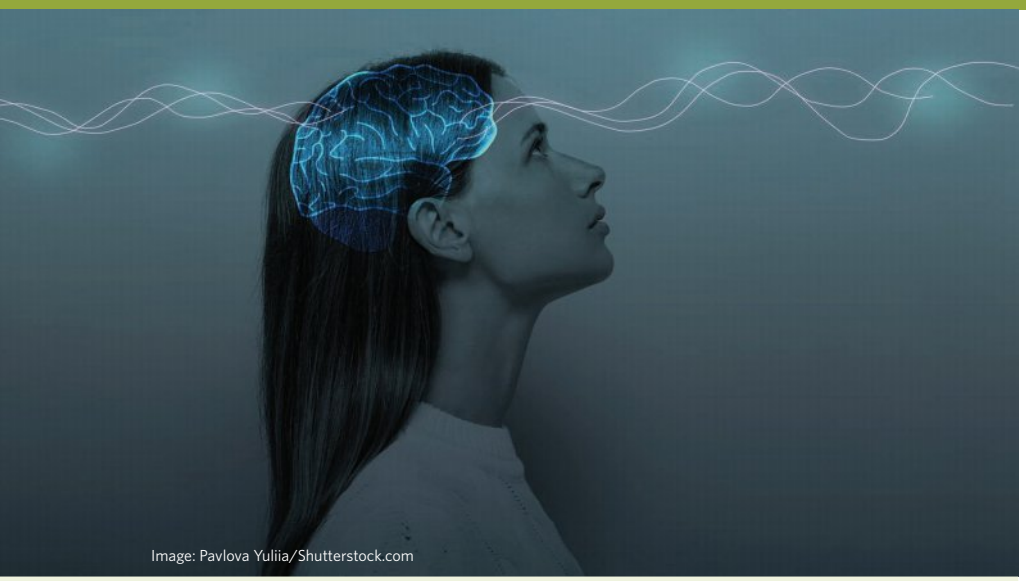


Image: Pavlova Yuliia/Shutterstock.com

How is dopamine assigned the name 4-(2-aminoethyl) benzene-1,2-diol?

All organic molecules, no matter how complicated, can be assigned a **systematic name**. In this lesson, we will discuss the **IUPAC naming** system and how it can be used to identify molecules, as well as **structural isomers** and the properties of organic compounds that affect their melting point, boiling point, and **viscosity**.

KEY TERMS AND DEFINITIONS

Dispersion forces weak intermolecular forces caused by attraction between instantaneous dipoles in adjacent molecules

Homologous series series of organic compounds that have the same general formula and similar chemical properties

Hydrogen bonding a type of permanent dipole-dipole attraction between molecules (not a covalent bond) that results from the attractive force between hydrogen atoms covalently bonded to a very electronegative atom such as an N, O, or F atom

Instantaneous dipole partial positive and negative charge that suddenly appears in an atom or molecule due to the random movement of electrons

IUPAC naming set of rules used to name organic compounds according to the International Union of Pure and Applied Chemistry (IUPAC)

Parent chain typically the longest continuous chain of carbon-carbon bonds, depending on the functional groups present

Permanent dipole a permanent area of partial positive or partial negative charge on a molecule due to differences in electronegativity between atoms within a molecule

Permanent dipole-dipole attraction electrostatic force of attraction between the permanent dipoles of adjacent polar molecules

Structural isomers molecules with the same molecular formula but different spatial arrangement of atoms

Systematic name standardised name used to identify organic compounds

Viscosity resistance of a substance to flow

STUDY DESIGN DOT POINTS

- the International Union of Pure and Applied Chemistry (IUPAC) systematic naming of organic compounds up to C8, with no more than two functional groups for a molecule, limited to non-cyclic hydrocarbons, haloalkanes, primary amines, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- characteristics of the carbon atom that contribute to the diversity of organic compounds formed, with reference to valence electron number, relative bond strength, relative stability of carbon bonds with other elements, degree of unsaturation, and the formation of structural isomers
- trends in physical properties within or between homologous series (boiling point and melting point, viscosity), with reference to structure and bonding

7A → 7B

- 4.1.3.1 Organic nomenclature
- 4.1.1.2 Structural isomers
- 4.1.4.1 Boiling and melting point
- 4.1.4.2 Viscosity

ESSENTIAL PRIOR KNOWLEDGE

- Intramolecular bonding and intermolecular forces
- Naming hydrocarbons

7A Structures of organic compounds

See questions 63–65.

Organic nomenclature 4.1.3.1

A set of naming conventions determined by the International Union of Pure and Applied Chemistry (IUPAC) provides a systematic method of naming any organic molecule.[1] Understanding the naming rules for organic compounds can help us determine the overall structure of the compounds.

KEEN TO INVESTIGATE?

[1] **How did the IUPAC come to be?** Search: IUPAC who we are our history industry and academia

USEFUL TIP

In carboxylic acids and primary amides, the carbon atom in the carbonyl group is always the first carbon in the parent carbon atom chain.

How is the parent carbon chain identified and numbered?

The **parent chain** is usually the longest continuous sequence of carbon-carbon bonds in a molecule. The number of carbon atoms in this chain is indicated by a prefix (table 1). Each carbon atom in the parent chain is numbered to determine the positions of any functional groups (figure 1). In unbranched hydrocarbons, the direction of this numbering is arbitrary as there are no functional groups to influence it. However, when functional groups are present, the direction of numbering is selected such that the numbers indicating the position of functional groups are as small as possible.

MISCONCEPTION

'Carbon-carbon double bonds are not functional groups.'

Carbon-carbon double bonds are alkene functional groups, as these affect the chemical properties of a molecule.

MISCONCEPTION

'The parent chain is always the longest sequence of carbon atoms.'

The parent chain is the longest sequence of bonded atoms that include the relevant functional groups. For example, all carboxyl groups must be part of the parent carbon chain.

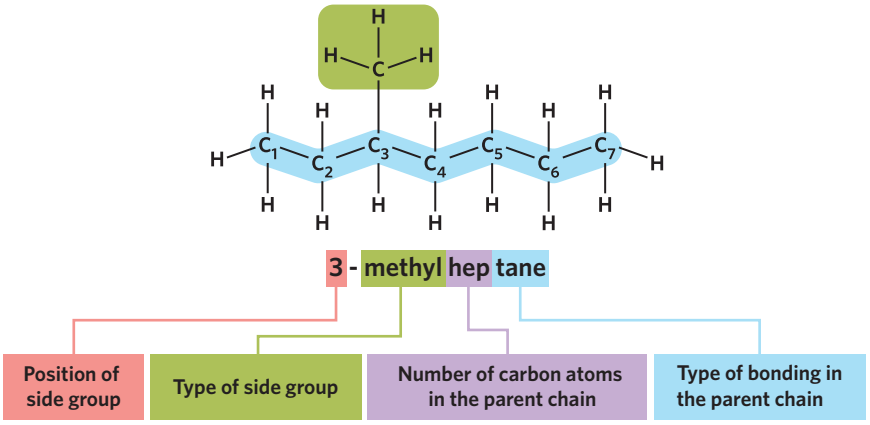


Figure 1 Numbering of the parent chain in a hydrocarbon

USEFUL TIP

The position of functional groups is not indicated when no other positions are possible. For example, as carboxyl groups occur at the terminal carbon of carboxylic acids, these do not require a number; i.e. 'butanoic acid'. Additionally, propene is never known as 'prop-1-ene' etc.

Table 1 Summary of the prefixes that represent different parent chain lengths in alkanes

Parent chain length	Parent chain prefix	Example
1	'meth-'	Methane
2	'eth-'	Ethane
3	'prop-'	Propane
4	'but-'	Butane
5	'pent-'	Pentane
6	'hex-'	Hexane
7	'hept-'	Heptane
8	'oct-'	Octane

MISCONCEPTION

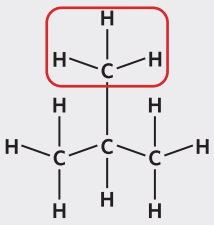
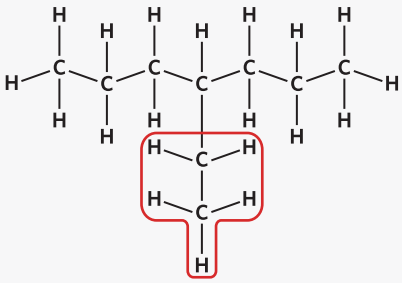
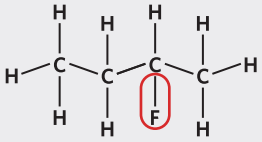
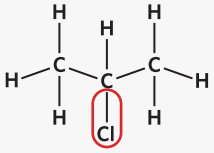
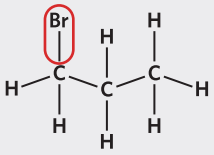
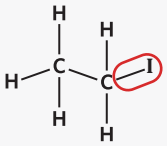
'Alkyl groups are functional groups.'

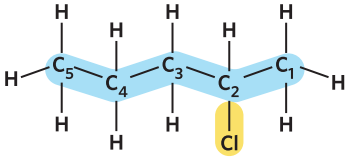
Functional groups affect the chemical properties of a compound. Alkyl groups only affect a molecule's physical properties (including melting and boiling point).

How are halogens and alkyl side chains named?

Halogens and side chains in branched organic compounds are also indicated using prefixes (table 2). As with other functional groups, their position is indicated by a number before their corresponding prefix (figure 2). When multiple of the same functional group or side chain are present, a counting prefix is included (table 3).

Table 2 Names of common alkyl branches and halogens

Parent chain length	Name	Example of structure	Name of structure
CH_3-	methyl-		methylpropane
CH_3CH_2-	ethyl-		4-ethylheptane
F–	fluoro-		2-fluorobutane
Cl–	chloro-		2-chloropropane
Br–	bromo-		1-bromopropane
I–	iodo-		iodoethane



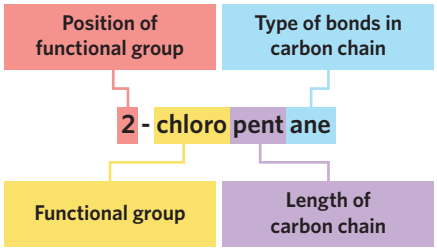


Figure 2 Indicating side chains and halogen groups

Table 3 Prefixes used to signify multiple of the same functional group

Number of times the same functional group is found in the molecule	Functional group prefix
2	di-
3	tri-
4	tetra-

WORKED EXAMPLE 1

What is the systematic name of the molecule with the following skeletal formula?



What information is presented in the question?

The skeletal formula for a molecule.

What is the question asking us to do?

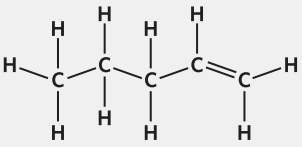
Provide the systematic name of the molecule shown.

What strategies do we need in order to answer the question?

1. Draw the structural formula for the molecule if needed.
2. Determine the longest carbon chain length.
3. Identify any side groups/double bonds present.
4. Identify the carbon number to which the side group/double bond is found.
5. Name the molecule.

Answer

If we imagine the full structural formula of this molecule, it would look like this:



The parent chain contains five carbon atoms. There is also a carbon-carbon double bond located at carbon number 1. Therefore, the systematic name of this molecule is pent-1-ene.

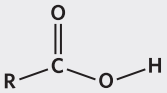
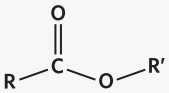
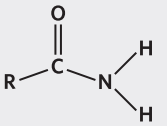
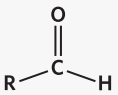
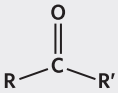
How are organic compounds with multiple different functional groups named?

For compounds with two functional groups, the suffix of the name of the compound is derived from the functional group with the highest priority, as outlined in table 4. The prefixes for the remaining functional group(s) are included earlier in the name in alphabetical order (figure 4).

Table 4 Hierarchy of functional groups as suffixes

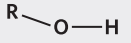
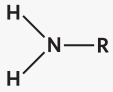
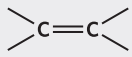
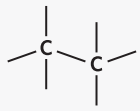
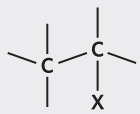
Highest priority as suffix

Lowest priority as suffix

Functional group	Type of compound	If used as prefix	If used as suffix
 (R represents an alkyl group)	Carboxylic acid	carboxy-*	-oic acid
 (R and R′ represent alkyl groups)	Ester	N/A	-yl -oate
 (R represents an alkyl group)	Primary amide	N/A	-amide
 (R represents an alkyl group)	Aldehyde	formyl-*	-al
 (R and R′ represent alkyl groups)	Ketone	oxo-*	-one

Continues →

Table 4 Continued

Functional group	Type of compound	If used as prefix	If used as suffix
 (R represents an alkyl group)	Alcohol	hydroxy-	-ol
 (R represents an alkyl group)	Amine	amino-	-amine
	Alkene	-en-	-ene
	Alkane	N/A	-ane
 (X represents a halogen)	Haloalkane	depends on halogen (table 2)	N/A

Highest priority as suffix

Lowest priority as suffix

*outside the scope of the VCE Study Design

How are IUPAC systematic names written overall?

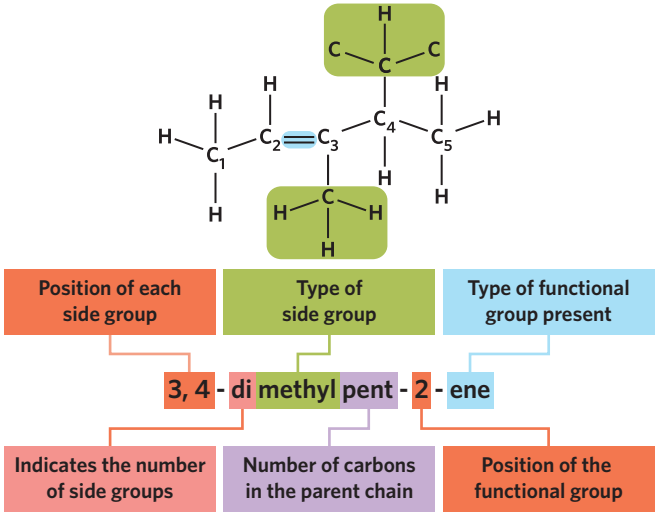


Figure 3 Naming with multiple functional groups

When writing the name of an organic compound, we need to ensure that we include the following conventions:

- Commas are used to separate numbers representing positions of functional groups.
- Hyphens (-) are used to separate numbers from words.
- There is no space between names of functional groups and the parent chain name.
- Prefixes indicating functional groups need to be written in alphabetical order (not including prefixes such as di, tri, etc.).

USEFUL TIP

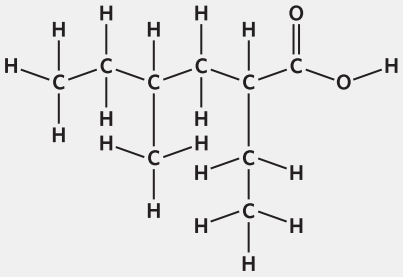
Molecules such as 'but-2-ene' may also be referred to as '2-butene'. Both naming conventions are accepted in VCAA exams.

USEFUL TIP

If the organic compound in figure 3 were incorrectly named '2,3-dimethylpent-3-ene' (counting from the other end of the parent carbon chain), the numbers in the name add to a lower total. However, in such cases, the functional group takes precedence and receives the lower possible number.

WORKED EXAMPLE 2

Identify the IUPAC name for the molecule shown.



What information is presented in the question?

The structural formula of a molecule.

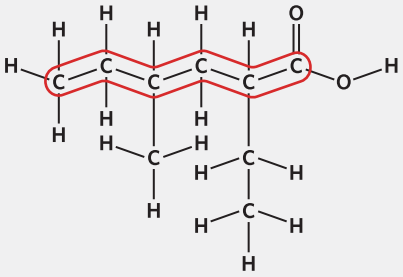
What is the question asking us to do?

Use the IUPAC naming system to name this molecule.

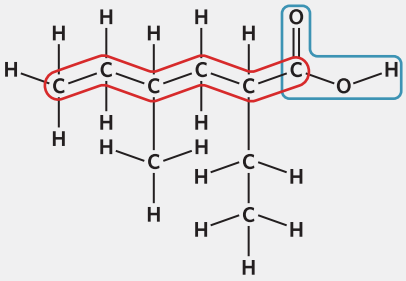
What strategies do we need in order to answer the question?

1. Identify and name the parent carbon chain.
2. Identify the type of organic compound and the appropriate suffix (ending) of its name.
3. Number the parent carbon chain.
4. Identify the number and position of any functional groups.
5. Identify the position and name of any side chains.
6. Write the complete name of the organic compound.

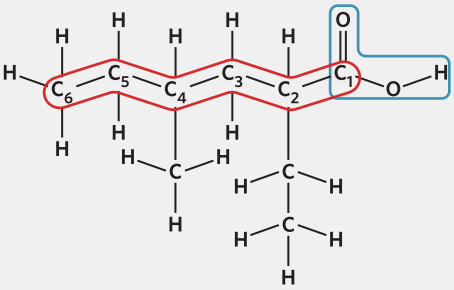
Answer



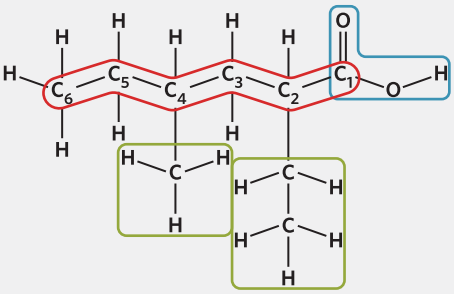
We can see that this is not the longest carbon-carbon chain. However, due to the presence of the carboxyl functional group, the parent chain must include this functional group. The chain identified in red is the longest carbon chain that includes the carboxyl functional group.



This molecule contains a carboxyl (−COOH) functional group. Therefore, the suffix for this molecule is '-oic acid'.



The terminal carbon closest to the functional group is marked as carbon number 1. In a carboxylic acid, the position of the −COOH group is always 1, meaning that the position does not need to be included in its name.



There are two alkyl groups (side chains) present - methyl and ethyl. The methyl group is bonded to carbon number 4 and the ethyl group is bonded to carbon number 2.

Therefore, the systematic name of this organic compound is 2-ethyl-4-methylhexanoic acid.

How are non-branched esters named?

Esters are formed during a condensation reaction between an alcohol and a carboxylic acid (lesson 8A). The IUPAC names of esters are determined by the number of carbon atoms on either side of their ester functional groups. The number of carbon atoms in each alkyl group gives the prefix that precedes each component of an ester's suffix, '-yl -oate'. The alkyl group that originally comes from the alcohol and is attached to the oxygen atom by a single bond is named first, followed by the carbon chain that includes the carbon atom in the carbonyl of the ester bond and comes from the carboxylic acid. For example, the ester shown in figure 4 has the systematic name 'propyl butanoate', which is formed by the condensation reaction between propanol and butanoic acid.

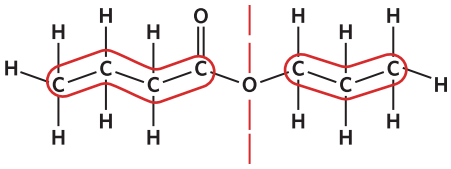


Figure 4 Structure of propyl butanoate

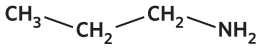
USEFUL TIP

You may come across a representation of a molecule that has features of both structural and semi-structural formulas (a structural formula that does not show all bonds). An example of this is shown in question 1.

PROGRESS QUESTIONS

Question 1

What is the correct IUPAC name for the compound shown?



A. Propan-1-amine
B. Ethanamine
C. 3-Propanamine
D. Propan-3-amine

Question 2

Which of the following is the correct systematic name for the compound with the semi-structural formula $CH_3CH_2CHCHCH_3$?

A. Pent-3-ene
B. Pent-2-ene
C. But-2-ene
D. Pentane

Structural isomers 4.1.1.2

Some chemical compounds have different names and structures but share the same molecular formula.

How can we determine the structural isomers of organic compounds?

Structural isomers are molecules that have the same molecular formula but differ in the spatial arrangement of their atoms. The three molecules in figure 5 have the same molecular formula, C_5H_{12}; however, their structural formulas differ, resulting in them having different names. In this example, pentane has a linear straight carbon chain, whilst methylbutane has a methyl group bonded to the second carbon of the linear carbon chain, and dimethylpropane has two methyl groups bonded to the central carbon atom of the parent carbon chain. Therefore, we can say that these three molecules are structural isomers of C_5H_{12}.

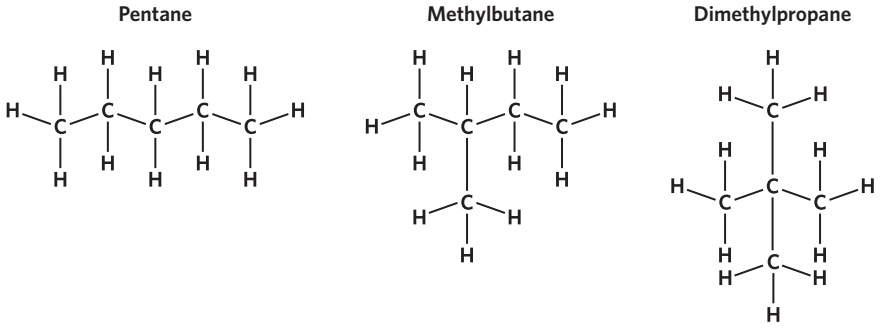


Figure 5 Structural isomers of C_5H_{12}

When it comes to larger molecules with more carbon atoms, it can be tricky to identify all of the possible structural isomers. There are some strategies that can be used to determine possible structural isomers of a molecule.

- Changing the position of a functional group or side chain
- Arranging available atoms into a branch/side chain
- Changing the identity of the functional group

WORKED EXAMPLE 3

How many structural isomers are there of C_4H_9Cl?

What information is presented in the question?

The molecular formula of the compound is C_4H_9Cl.

What is the question asking us to do?

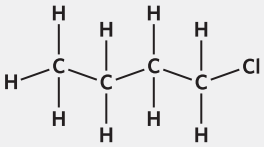
Determine the number of possible structural isomers of C_4H_9Cl.

What strategies do we need in order to answer the question?

1. Draw a straight chain structure of a molecule with the formula C_4H_9Cl.
2. Identify if the halogen can be attached to other carbon atoms in the chain.
3. Identify if any side chains can be made from the atoms available.
4. Draw the different possible structures based on the details given.

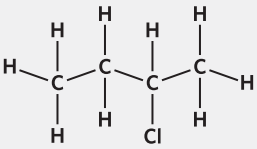
Answer

Straight chain structure



1-chlorobutane

Moving the position of the halogen

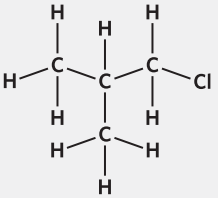


2-chlorobutane

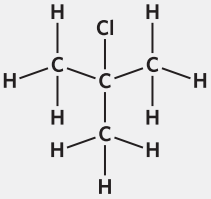
If we continue to shift Cl to the carbon atoms on the left, we would be recreating both 1-chlorobutane and 2-chlorobutane.

Possible alkyl groups

We can rearrange atoms to make a methyl group with a three carbon parent chain.



1-chloromethylpropane



2-chloromethylpropane

Therefore, there are four structural isomers for C_4H_9Cl.

Adapted from VCAA 2012 Exam 1 Multiple choice Q2

PROGRESS QUESTIONS

Question 3

The compound that is **not** an isomer of 2,2,4-trimethylpentane is

A. octane.

B. 3-ethylhexane.

C. 2,4-dimethylpentane.

D. 2,4-dimethylhexane.

VCAA 2011 Exam 1 Multiple choice Q4

Boiling and melting point 4.1.4.1

The boiling point of a compound can give important information about the physical properties and structural characteristics of the compound, both between and within **homologous series** (sets of compounds that differ only by the length of their carbon chain).

What intermolecular forces act between molecules?

Dispersion forces, permanent dipole-dipole attraction, and **hydrogen bonding** are intermolecular forces that electrostatically attract molecules to each other. These are determined by their structure, including the presence of functional groups, level of branching, and degree of saturation.

Dispersion forces

Due to their constant movement, there are moments when electrons in a molecule will concentrate in one region, creating an area of slightly negative charge and one with a slightly positive charge. This is known as an **instantaneous dipole**. Dispersion forces arise between atoms in adjacent molecules as a result of electrostatic attraction between instantaneous dipoles.

The more electrons a molecule has, the greater the possibility that an instantaneous dipole will form and induce another dipole in a nearby molecule. This means that there are stronger dispersion forces between larger molecules (greater surface area with more electrons) than smaller molecules (smaller surface area with fewer electrons), as shown in figure 6. The surface area of a molecule also increases with reduced branching and increased saturation (able to pack together more tightly) and increased saturation (less 'kinks' and more C—H bonds).
Therefore, dispersion forces increase with:

- increase in carbon chain length
- reduced branching
- increased saturation.

Dispersion forces are the weakest intermolecular force in VCE chemistry, and all organic compounds experience dispersion forces between their molecules. The following types of organic compounds experience only dispersion forces between molecules.

- Alkanes
- Alkenes

Permanent dipole-dipole attraction

Permanent dipole-dipole attractions only occur between polar molecules (which contain **permanent dipoles** (figure 7)), and not between symmetrical non-polar molecules with a polar bond. Permanent dipole-dipole attractions are considerably harder to disrupt than dispersion forces, as the attractive forces between molecules are greater. The strength of a permanent dipole-dipole attraction depends on the difference in electronegativity of the atoms involved in the relevant polar bonds.

MISCONCEPTION

'Molecules with polar bonds always experience strong permanent dipole-dipole attraction.'

Only polar molecules experience dipole-dipole attraction. Recall from 7A that molecules that contain a polar bond are not necessarily polar overall. Fatty acids, which contain a carboxyl group but are mainly composed of a nonpolar tail, mainly experience dispersion forces and relatively weak dipole-dipole attraction despite their polar C=O and highly polar O–H bond.

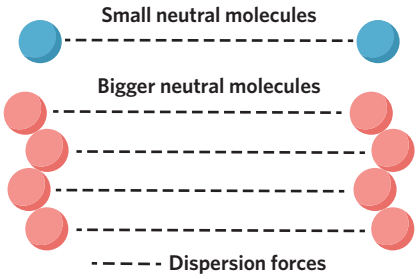


Figure 6 Dispersion forces between molecules of different sizes

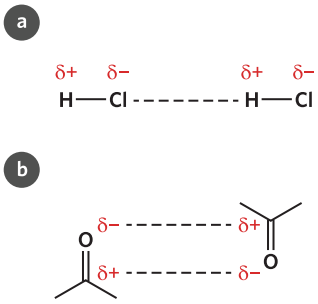


Figure 7 Permanent dipole-dipole forces between **(a)** HCl molecules and **(b)** polar carbonyl groups in propanone

MISCONCEPTION

'A hydrogen bond is a type of chemical bond.'

Hydrogen bonds are not chemical bonds; they are forces of electrostatic attraction between adjacent molecules. Chemical bonds are formed by electrostatic attraction between atoms within a compound.

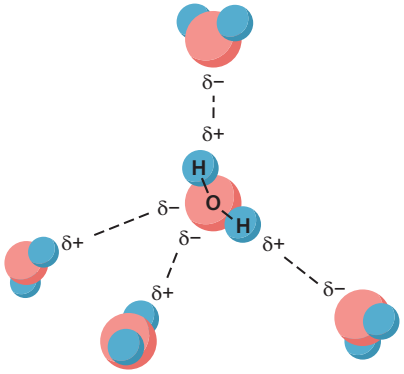


Figure 8 Hydrogen bonding between water molecules

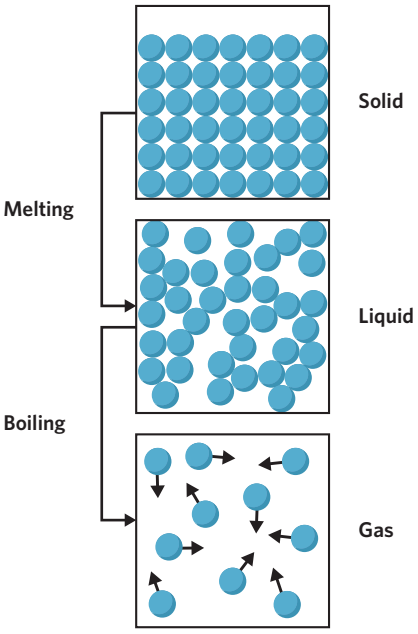


Figure 9 Arrangement of molecules in different states of matter

USEFUL TIP

In general, the strength of intermolecular forces within molecules of a substance increases according to the order:

Hydrocarbons < Esters, Aldehydes, Ketones, Amines < Alcohols < Carboxylic acids < Amides

The following organic compounds experience permanent dipole-dipole attraction in addition to dispersion forces.

- Aldehydes (polar C=O bond)
- Ketones (polar C=O bond)
- Esters (polar C=O bond)
- Haloalkanes (polar C−X bond, where X represents a halogen)

Hydrogen bonding

Hydrogen bonding is a type of permanent dipole-dipole attraction that only occurs between molecules in which hydrogen is bonded directly to either nitrogen, oxygen, or fluorine.

A common occurrence of hydrogen bonding is between water molecules, as shown in figure 8. In all instances of hydrogen bonding, the hydrogen atom has a partial positive charge and is attracted to a nitrogen, oxygen, or fluorine atom with a partial negative charge on an adjacent molecule.

The considerable difference in electronegativity between hydrogen and these elements creates a highly polar bond. In turn, this means that the electrostatic attraction between the permanent dipoles is stronger than those observed in typical dipole interactions.

The following organic compounds experience hydrogen bonding in addition to dispersion forces.

- Alcohols (highly polar O−H bond)
- Carboxylic acids (highly polar O−H bond) (also experience dipole-dipole interactions due to C=O bond)
- Primary amines (highly polar N−H bonds)
- Primary amides (highly polar N−H bonds) (also experience dipole-dipole interactions due to C=O bond)

Why do some compounds have higher boiling and melting points than others?

The boiling point of a liquid is defined as the temperature at which it changes from its liquid state to a gaseous state. Similarly, the melting point of a solid is the temperature at which it transitions from a solid to a liquid state (figure 9). Each of these changes involves the intermolecular forces that hold molecules together being overcome, which requires an input of energy. The stronger the electrostatic attraction between molecules, the more energy (often heat, or thermal energy) required to overcome these. For example, amides have very high boiling and melting points due to the strong hydrogen bonding and dipole-dipole attraction between adjacent molecules (figure 10). The boiling and melting points of mixtures and pure substances will be discussed further in lesson 9B.

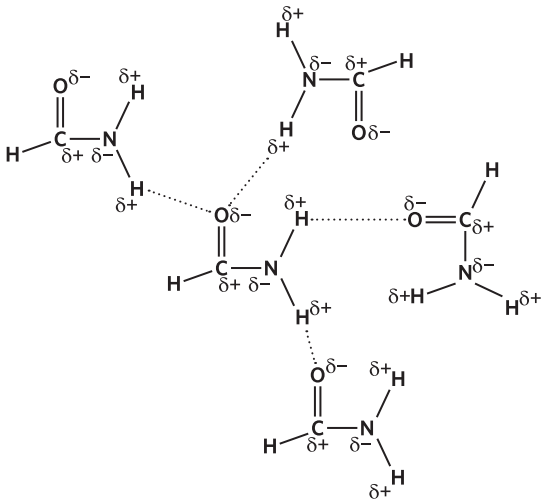
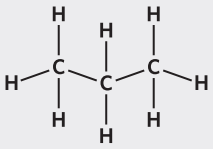
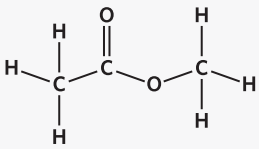
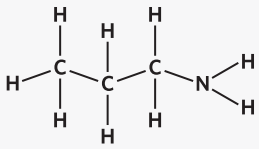
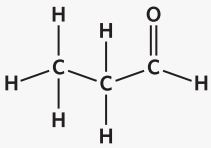
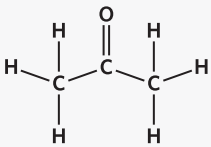
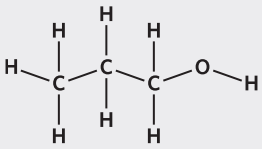
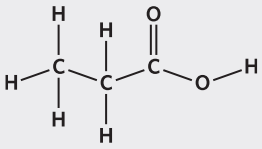
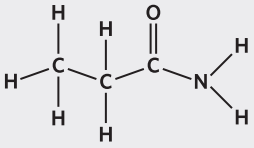


Figure 10 Intermolecular forces between methanamide molecules

Table 5 shows how the structure of molecules affects their properties.

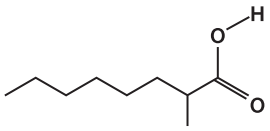
Table 5 The influence of intermolecular forces on the physical properties of molecules

Molecule (given same number of carbon atoms) and strength of intermolecular forces	Structure	Intermolecular forces	Melting point (°C)	Boiling point (°C)
Weakest: Hydrocarbons	Propane 	Dispersion forces	−188	−42
Intermediate: In no particular order: • Esters • Amines • Aldehydes • Ketones	Methyl ethanoate 	Dispersion forces, permanent dipole-dipole attraction (C=O)	−98	52
	Propan-1-amine 	Dispersion forces, hydrogen bonding (N−H)	−83	48
	Propanal 	Dispersion forces, permanent dipole-dipole attraction (C=O)	−80	49
	Propanone 	Dispersion forces, permanent dipole-dipole attraction (C=O)	−95	56
Strongest: • Alcohols • Carboxylic acids • Amides	Propan-1-ol 	Dispersion forces, hydrogen bonding (O−H)	−126	97
	Propanoic acid 	Dispersion forces, permanent dipole-dipole attraction (C=O), hydrogen bonding (O−H)	−21	141
	Propanamide 	Dispersion forces, permanent dipole-dipole attraction (C=O), hydrogen bonding (N−H)	176	213

PROGRESS QUESTIONS

Question 4

Which is the strongest type of attraction that exists between the molecules of this substance?



A. Dispersion forces

B. Dipole-dipole forces

C. Hydrogen bonding

D. Covalent bonding

Question 5

Consider compounds 1 and 2, which are saturated molecules that contain the same number of carbon atoms.

Compound 1



Compound 2



Which of the following gives the compound expected to have a lower boiling point, and why?

A. Compound 1, because it experiences stronger dispersion forces between molecules

B. Compound 2, because it experiences stronger dispersion forces between molecules

C. Compound 1, because it experiences weaker dispersion forces between molecules

D. Compound 2, because it experiences weaker dispersion forces between molecules

Viscosity 4.1.4.2

USEFUL TIP

As melting and boiling points increase, so does viscosity.

Viscosity can give an indication of the physical and structural characteristics of organic compounds.

Why are some compounds more viscous than others?

Viscosity measures a substance's resistance to flow and reflects the substance's structural properties. Liquids with high viscosity, like honey, flow very slowly, whilst those with low viscosities, like water, flow more readily (figure 11). This is due to the strength of the intermolecular forces between their molecules.

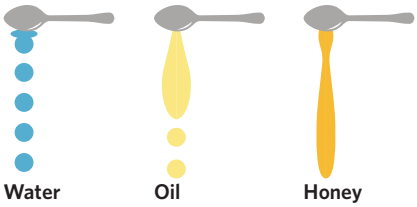


Figure 11 Viscosity of some common substances

The viscosity of liquids depends on the interactions between molecules, increasing as the forces of attraction between molecules increase. As shown in figure 12, liquids with stronger intermolecular forces, like honey, have stronger attractive forces holding the molecules together, making it harder for the substance to flow. Conversely, non-polar substances that mainly experience dispersion forces, like cooking oil, tend to be less viscous because their intermolecular forces are weaker, allowing them to flow more readily in comparison.

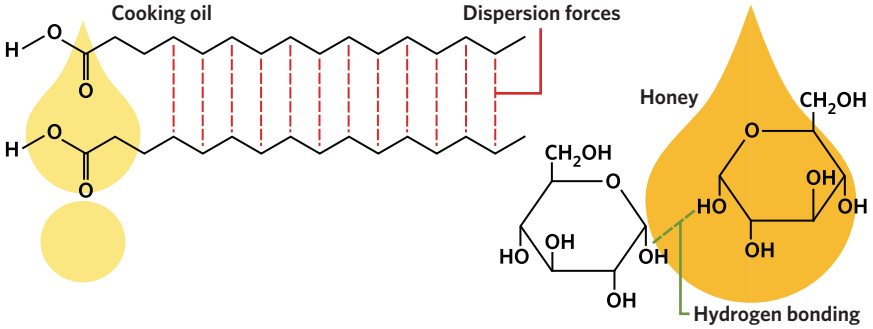


Figure 12 Intermolecular forces between molecules in cooking oil and honey

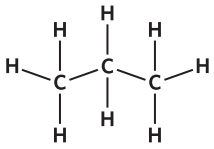
As viscosity is dependent on the intermolecular reactions between molecules, changes in temperature (and hence thermal energy) can affect the ability of substances to flow. An increase in temperature results in a decrease in viscosity as there is more energy available to overcome these forces, allowing substances to flow more readily. Conversely, a decrease in temperature results in an increase in viscosity.

PROGRESS QUESTIONS

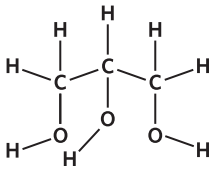
Question 6

Which of the following correctly lists these compounds in order of decreasing ability to flow?

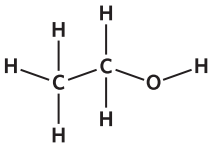
Compound 1



Compound 2



Compound 3



A. Compound 1, compound 2, compound 3

B. Compound 2, compound 3, compound 1

C. Compound 3, compound 2, compound 1

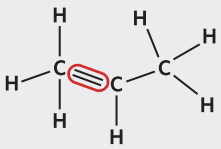
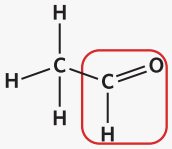
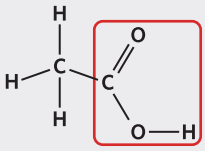
D. Compound 1, compound 3, compound 2

Theory summary

- To name all organic compounds, we need to go through 6 steps.
  1. Identify and name the parent carbon chain.
  2. Identify the type of the organic compound and ending of its name.
  3. Number the parent carbon chain.
  4. Identify the number and position(s) of any functional groups and/or side chain(s).
  5. Identify the name of any functional groups and/or side chain(s).
  6. Write the complete name of the organic compound.
- If a compound has two or more functional groups or branches, the parent carbon chain is determined based on the priorities of functional groups.
- Structural isomers are compounds that have the same molecular formula but differ in their structure (and name).
- The strength of dispersion forces increases with increased surface area of molecules.

- Trends of boiling point, melting point, and viscosity:

Melting point, boiling point, viscosity increase ↓

Types of organic compounds	Example	Intermolecular forces (experienced by the example)	Polarity
Alkanes, alkenes	Propene 	Dispersion forces	Non-polar
Haloalkanes (C–X), aldehydes (C=O), ketones (C=O), esters (C=O)	Ethanal 	Permanent dipole-dipole bonding (C=O), dispersion forces	Polar
Alcohols (O–H), primary amines (N–H), primary amides (N–H), carboxylic acids (O–H)	Ethanoic acid 	Hydrogen bonding (O–H), permanent dipole-dipole attraction (C=O), dispersion forces	Polar

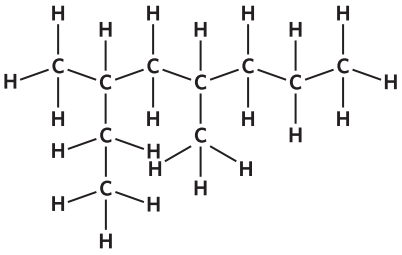
7B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

Consider the following structural formula of an organic compound.



Question 7 (1 MARK)

How many carbon atoms are in the parent carbon chain?

A. 6 **B.** 7 **C.** 8 **D.** 9

Question 8 (1 MARK)

Which option represents the correct (lowest cumulative) positions and names of the branches in the compound shown?

A. 1-methyl **B.** 3,5-dimethyl **C.** 4,6-dimethyl **D.** 4-ethyl-2-methyl

Question 9 (1 MARK)

What is the IUPAC name for the organic compound shown?

Exam-style

Question 10 (3 MARKS)

Draw the structural formulas for the following organic compounds.

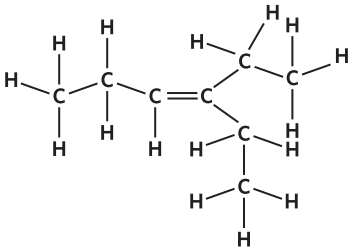
a. 2,4-dimethylpent-2-ene 1 MARK

b. 3-aminopropanoic acid 1 MARK

c. 3-bromopentan-2-ol 1 MARK

Question 11 (1 MARK)

Compared to many of the other isomers of the molecule shown, this structural isomer has a relatively low melting point.

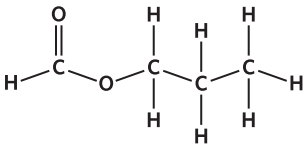


Why does this molecule have a lower melting point than its other isomers?

Question 12 (5 MARKS)

Write the correct IUPAC name for the compounds shown.

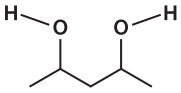
a.



1 MARK

b. $CH_2CHCH(CH_3)CH(CH_3)CH_3$ 1 MARK

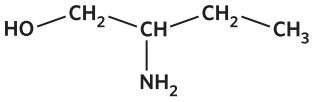
c.



1 MARK

d. $CH_3CH(Br)CH(Br)CH_3$ 1 MARK

e.

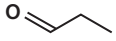


1 MARK

Question 13 (2 MARKS)

There are a number of structural isomers with the molecular formula C_3H_6O. Three of these are propanal, propanone, and prop-2-en-1-ol.

The skeletal structure for the aldehyde propanal is shown.



a. Write the semi-structural formula for the ketone isomer propanone. 1 MARK

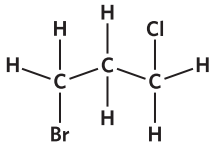
b. Draw the structural formula for the isomer prop-2-en-1-ol. 1 MARK

VCAA 2017 exam Short answer Q5a

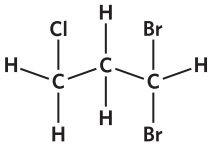
Question 14 (1 MARK)

Which of the following gives the correct systematic names for organic compounds I and II respectively?

I.



II.



A. 1-bromo-3-chloropropane and 1,1-dibromo-3-chloropropane

B. 3-chloro-1-bromopropane and 3-chloro-1,1-dibromopropane

C. 1-bromo-3-chloropropane and 3-chloro-1,1-dibromopropane

D. 1-chloro-3-bromopropane and 1,1-dibromo-3-chloropropane

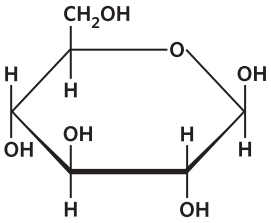
Question 15 (6 MARKS)

Draw all non-cyclic structural isomers of C_4H_8 and give the IUPAC name for each isomer.

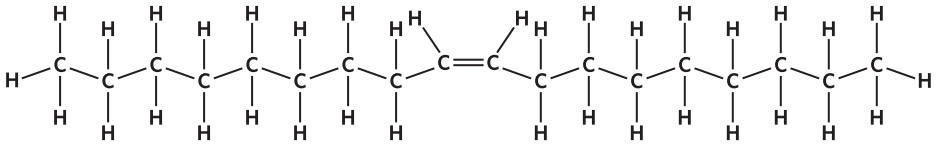
Question 16 (3 MARKS)

Explain why a substance made up of molecule I is more resistant to flow than a substance made up of molecule II.

Molecule I

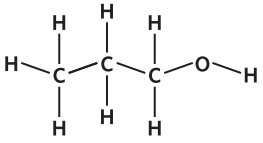
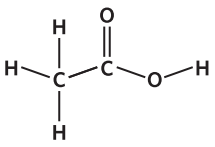
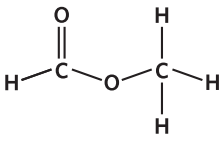


Molecule II



Question 17 (1 MARK)

The table shows information about three organic compounds.

Compound	Structural formula	Molecular mass (g mol^{-1})	Boiling point (°C)
X		60	97
Y		60	118
Z		60	?

What is the best estimate for the boiling point of compound Z?

A. 31 °C **B.** 101 °C **C.** 114 °C **D.** 136 °C

VCAA 2020 exam Multiple choice Q16

Question 18 (1 MARK)

For which one of the following molecular formulas is there only one possible structure?

A. C_3H_7OH **B.** $C_2H_2F_2$ **C.** C_4H_8 **D.** C_2HF_3

Key science skills

Question 19 (9 MARKS)

Soybean biodiesel is biodiesel that is produced from soybeans. Two students developed a method to investigate the effect of temperature on the viscosity of soybean biodiesel and petrodiesel (long straight-chain hydrocarbons derived from fossil fuel). The students' method is given.

Aim

To determine how temperature affects the viscosity of soybean biodiesel and petrodiesel.

Method

1. Set up four water baths at temperatures of 10 °C, 20 °C, 30 °C, and 40 °C.
2. Label four 250 mL beakers with 'soybean biodiesel'. Add about 120 mL of soybean biodiesel to each beaker and then place one beaker into each of the four water baths.
3. Label four 250 mL beakers with 'petrodiesel'. Add about 120 mL of soybean biodiesel to each beaker and then place one beaker into each of the four water baths.
4. Use a 100 mL measuring cylinder to collect approximately 50 mL of soybean biodiesel from the 10 °C water bath.
5. Close the burette tap and fill the burette with the soybean biodiesel. Record the initial volume of soybean biodiesel from the burette.
6. Open the burette tap and use a stopwatch to measure the time it takes to deliver 20.00 mL of soybean biodiesel from the burette.
7. Repeat step 6 to obtain two more measurements at the same temperature. (Refill the burette with soybean biodiesel as necessary.)
8. Repeat steps 4 to 7 with the soybean biodiesel from the 20 °C, 30 °C, and 40 °C water baths.
9. Repeat steps 4 to 7 with petrodiesel from the 10 °C, 20 °C, 30 °C, and 40 °C water baths.

a. How should the students safely dispose of the waste petrodiesel? 1 MARK

b. Identify the dependent variable in this investigation. 1 MARK

c. Consider the variables in the investigation.

i. State a variable that has not been controlled in the method used by the students. 1 MARK

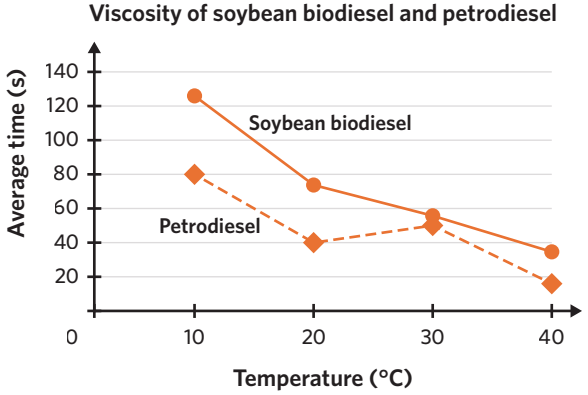
ii. Explain the impact that the variable in part **c.i.** has on the dependent variable. 2 MARKS

d. The two students performed the investigation independently. Some of the data collected by the first student is given in the table provided.

Temperature (°C)	Time (s)					
	Trial 1		Trial 2		Trial 3	
	Soybean biodiesel	Petrodiesel	Soybean biodiesel	Petrodiesel	Soybean biodiesel	Petrodiesel
10	123	74	116	70	130	66

Explain what the data in the table indicates about the relative viscosity of soybean biodiesel and petrodiesel. 2 MARKS

e. The student drew the graph shown to represent their data.



i. Identify the trend in the results for soybean biodiesel shown in the graph. 1 MARK

ii. Suggest **one** reason, related to the method used by the students, for the outlier at 30 °C for petrodiesel. 1 MARK

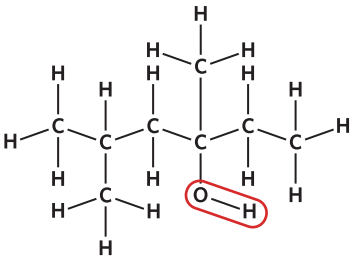
VCAA (NHT) 2022 exam Short answer Q9

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

Question 20 (4 MARKS)

For the molecule shown:



a. Identify the functional group circled. 1 MARK

b. What type of alcohol can this compound be classified as? Explain. 2 MARKS

c. What is the name of this compound? 1 MARK

FROM LESSON 7A

Question 21 (1 MARK)

A student wants to use a physical property to distinguish between two alcohols, octan-1-ol and propan-1-ol. Both alcohols are colourless liquids at standard laboratory conditions (SLC).

The student should use

A. density because propan-1-ol has a much higher density than octan-1-ol.

B. boiling point because octan-1-ol has a higher boiling point than propan-1-ol.

C. electrical conductivity because octan-1-ol has a higher conductivity than propan-1-ol.

D. energy released during combustion because propan-1-ol has a higher specific heat capacity than octan-1-ol.

VCAA 2018 exam Multiple choice Q21

FROM LESSONS 7A & 2B

Question 22 (1 MARK)

Which one of the following fuels is expected to have the highest viscosity at SLC?

A. Ethanol

B. Bioethanol

C. Biodiesel

D. Petrol

VCAA (NHT) 2021 exam Multiple choice Q8

FROM LESSONS 1A & 1B

Chapter 7 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which statement is correct about the structure of alkanes?

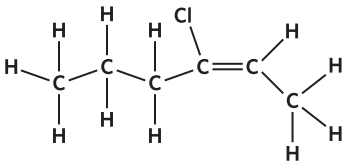
A. An alkane is an unsaturated hydrocarbon.

B. Alkanes have only single carbon-carbon bonds in their structures.

C. The general formula for alkanes is C_nH_{2n}.

D. Alkanes have single and double carbon-carbon bonds in their structures.

Question 2 (1 MARK)



The correct systematic name for the compound shown is

A. 2-chlorohex-2-ene.

B. 3-chlorohex-2-ene.

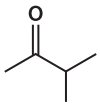
C. 3-chlorohex-3-ene.

D. 4-chlorohex-5-ene.

VCAA 2012 Exam 1 Multiple choice Q1

Question 3 (1 MARK)

A compound has the following skeletal formula.



The molar mass and classification of the compound are, respectively

A. 71 g mol^{-1}, aldehyde.

B. 74 g mol^{-1}, aldehyde.

C. 85 g mol^{-1}, ketone.

D. 86 g mol^{-1}, ketone.

Adapted from VCAA 2019 exam Multiple choice Q3

Question 4 (1 MARK)

The systematic name of $CH_3CH_2CH(CH_3)CH(CH_3)CH_2CH_3$ is

A. 2-ethyl-3-methylpentane.

B. 3-methyl-4-ethylpentane.

C. 3,4-dimethylhexane.

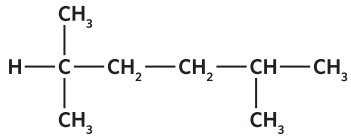
D. 2,3-diethylbutane.

Adapted from VCAA 2010 Exam 1 Multiple choice Q10

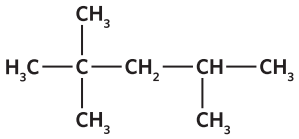
Question 5 (1 MARK)

Consider the following structures.

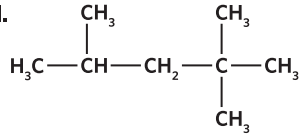
I.



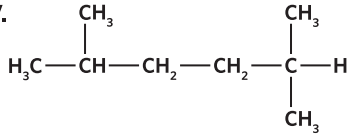
II.



III.



IV.



Which of the structures is that of 2,2,4-trimethylpentane?

A. I and III only **B.** I and IV only **C.** II and III only **D.** II and IV only

VCAA 2011 Exam 1 Multiple choice Q3

Question 6 (1 MARK)

Petrodiesel is a fuel made up of a number of different molecules, including $C_{12}H_{26}$. Biodiesel is often made up of $C_{11}H_{22}O_2$, which contains an ester group.

When comparing $C_{12}H_{26}$ and $C_{11}H_{22}O_2$, which one of the following statements is correct?

A. $C_{12}H_{26}$ has a higher viscosity due to the dispersion forces between the molecules.

B. $C_{12}H_{26}$ has a higher boiling point due to dipole-dipole attraction between molecules.

C. $C_{11}H_{22}O_2$ has a higher viscosity due to hydrogen bonding between the molecules.

D. $C_{11}H_{22}O_2$ has a higher boiling point due to dipole-dipole attraction between molecules.

Adapted from VCAA 2020 exam Multiple choice Q25

Question 7 (1 MARK)

The number of unbranched esters that have a molecular formula of $C_4H_8O_2$ is

A. 2 **B.** 3 **C.** 4 **D.** 5

VCAA (NHT) 2021 exam Multiple choice Q19

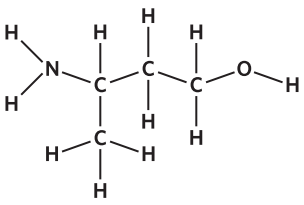
Question 8 (1 MARK)

Which of these is **not** the correct IUPAC nomenclature for an isomer of 1-chloropent-2-ene?

A. 4-chloropent-2-ene **B.** 3-chloropent-1-ene **C.** 5-chloropent-1-ene **D.** 1-chloropent-3-ene

---

Question 9 (1 MARK)



What is the IUPAC systematic name for the molecule shown?

A. 3-aminobutan-1-ol

B. 4-hydroxybutan-2-amine

C. 3-methyl-3-aminopropan-1-ol

D. 3-hydroxy-1-methylpropan-1-amine

VCAA (NHT) 2021 exam Multiple choice Q11

Question 10 (1 MARK)

One mole of methane, CH_4, reacts with one mole of an unknown halogen, X_2. X could be fluorine, F, chlorine, Cl, or bromine, Br. The general equation for the reaction is shown.

$$CH_4(g) + X_2(g) \xrightarrow{\text{catalyst}} CH_3X(g) + HX(g) \quad \Delta H < 0$$

Which of the following statements is true?

A. The strength of the bonds from weakest to strongest is C—Br < C—Cl < C—F.

B. Since hydrogen has the smallest atomic radius, the C—H bond is the weakest bond.

C. The C—Br bond is stronger than the C—H bond because of the size of the bromine atom.

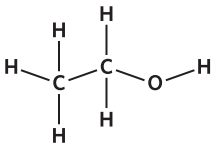
D. The C—Br, C—Cl and C—F bonds are equal in strength because Br, Cl, and F are all halogens.

VCAA 2022 exam Multiple choice Q29

Short answer (30 MARKS)

Question 11 (6 MARKS)

Organic compounds are classified according to the IUPAC nomenclature guidelines.



a. What is the systematic name for the compound shown? 1 MARK

b. Write the semi-structural (condensed) formula for propyl methanoate. 1 MARK

c. Draw the structural formula for 2-methylpropanal. 1 MARK

d. What homologous series does 2-methylpropanal belong? 1 MARK

e. Draw the skeletal formula for butanamide. 1 MARK

f. Write the IUPAC name for a secondary alcohol with molecular formula C_3H_7OH. 1 MARK

Question 12 (3 MARKS)

Carboxylic acids can have esters as structural isomers.

a. Draw the skeletal formula for propanoic acid. 1 MARK

b. There are two unbranched esters that are structural isomers of propanoic acid.

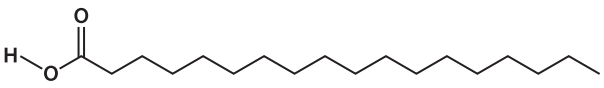
i. Draw the structural formula for one of these isomers. 1 MARK

ii. Give the IUPAC name for this isomer. 1 MARK

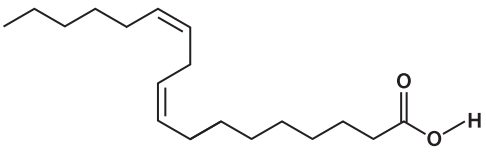
Question 13 (5 MARKS)

Olive oil contains a mixture of saturated and unsaturated hydrocarbons known as fatty acids.

A.



B.

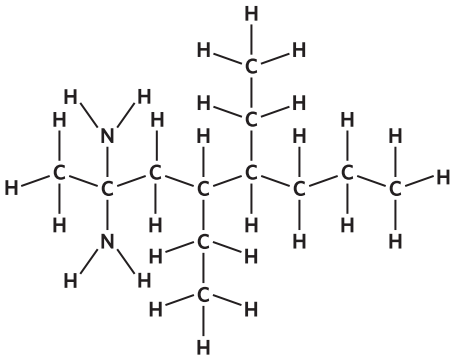


a. Which of the following structures shows an unsaturated molecule? Explain. 2 MARKS

b. A sample of which of these molecules would be expected to have a lower boiling point? Explain. 3 MARKS

Question 14 (1 MARK)

What is the IUPAC name for the organic compound shown?



Question 15 (3 MARKS)

The semi-structural formulas of two fatty acids are shown. Which of the fatty acids – oleic acid or linoleic acid – would be expected to have a lower melting point? Justify your answer.

Oleic acid: $CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$

Linoleic acid: $CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$

Adapted from VCAA 2021 exam Short answer Q3dii

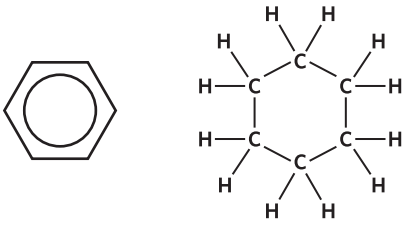
Question 16 (4 MARKS)

Draw all structural isomers of $C_4H_{11}OH$, and label them as primary, secondary, or tertiary alcohols.

Question 17 (3 MARKS)

A chemistry student wishes to determine which of cyclohexane and benzene has melting point 5.5 °C and which has melting point 6.5 °C. The structures of cyclohexane and benzene are shown.

Benzene **Cyclohexane**



Which of these organic molecules is expected to have each melting point? Explain.

Question 18 (5 MARKS)

A driver has been testing two different trucks running on two different fuel sources: petrodiesel (a fossil fuel composed of a mixture of hydrocarbons) and biodiesel (a renewable fuel made of molecules that contain an ester functional group).

When they were driving their biodiesel truck through a cold region, they noticed that the fuel was not flowing along the fuel line as well when compared to a warmer region.

a. With reference to viscosity and flow along fuel lines, suggest a reason why this was the case. 2 MARKS

b. They also discovered that biodiesel has a higher boiling point. Using your knowledge of structure and bonding, explain this difference in boiling point. 3 MARKS

Key science skills (10 MARKS)

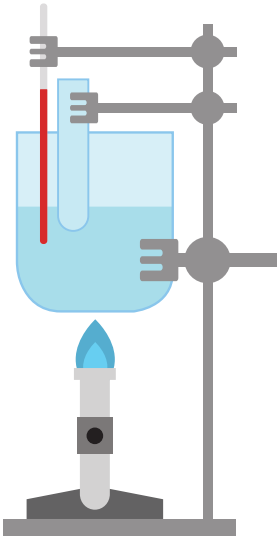
Question 19 (4 MARKS)

A chemistry class was asked to conduct an experiment to determine the effect of molecular structure on the properties of organic compounds. Each pair of students was given two samples of organic compounds, both with the molecular formula of C_5H_{12} but with different structures.

Materials

- Retort stand
- 3 × clamps
- 1 pre-calibrated thermometer
- 250 mL beaker
- Bunsen burner
- Sample A
- Sample B
- 2 × test tubes
- Measuring cylinder

The experimental setup is shown.



Method

1. Place 2 mL of sample A into a test tube and attach it to the retort stand via a clamp.
2. Fill a beaker with 150 mL of water and place it on a stand above the bunsen burner.
3. Slowly lower the test tube into the beaker, making sure that it does not touch the bottom of the beaker.
4. Place a thermometer into the test tube and hold it in place via a clamp attached to the retort stand.
5. Turn on the bunsen burner and keep it on until the sample boils.
6. Turn off the bunsen burner and record the temperature.
7. Repeat steps 1–6 for sample B.

Results

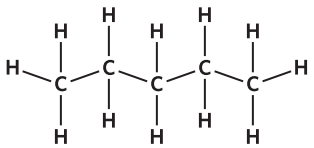
	Sample A	Sample B
Boiling point (°C)	31.1	10.2

a. Identify the dependent variable in this experiment. 1 MARK

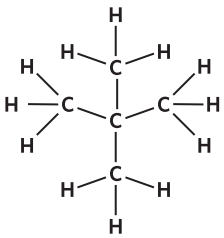
b. Identify the cause of a systematic error that could occur during this experiment. 1 MARK

c. The students were given the two molecular structures shown and were told that each structure represents one of the samples used.

Structure 1



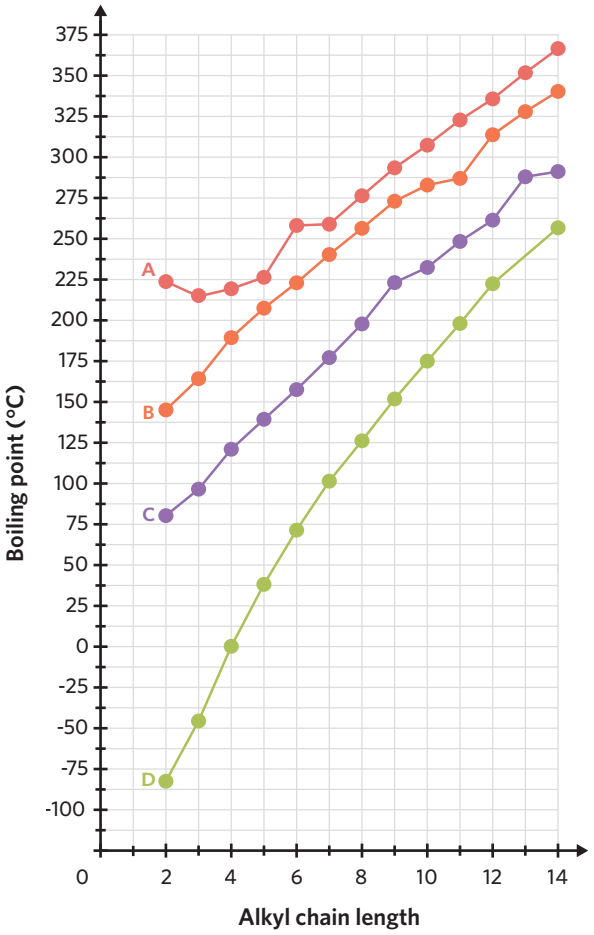
Structure 2



Based on the results, which of the structures would belong to each sample? Explain. 2 MARKS

FROM LESSONS 12B & 12D

Question 20 (6 MARKS)



The graph provided shows the boiling points of organic molecules from different homologous series in terms of their alkyl chain length. It is known that in no particular order, A, B, C, and D represent alkanes, primary alcohols, primary amides, and carboxylic acids.

a. Identify homologous series A, B, C, and D, and the intermolecular forces between the molecules in each homologous series. 4 MARKS

b. Identify and explain the trend in boiling point of species within the homologous series shown. 2 MARKS

FROM LESSON 12C

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8

CHAPTER 8
Reactions of organic compounds

LESSONS

8A Types of organic reactions

8B Sustainability of the production of chemicals

Chapter 8 review

KEY KNOWLEDGE

- organic reactions and pathways, including equations, reactants, products, reaction conditions and catalysts (specific enzymes not required):
  - synthesis of primary haloalkanes and primary alcohols by substitution
  - addition reactions of alkenes
  - the esterification between an alcohol and a carboxylic acid
  - hydrolysis of esters
  - pathways for the synthesis of primary amines and carboxylic acids
  - transesterification of plant triglycerides using alcohols to produce biodiesel
  - hydrolytic reactions of proteins, carbohydrates and fats and oils to break down large biomolecules in food to produce smaller molecules
  - condensation reactions to synthesise large biologically important molecules for storage as proteins, starch, glycogen and lipids (fats and oils)
- calculations of percentage yield and atom economy of single-step or overall reaction pathways, and the advantages for society and for industry of developing chemical processes with a high atom economy
- the sustainability of the production of chemicals, with reference to the green chemistry principles of use of renewable feedstocks, catalysis and designing safer chemicals

Image: Rattiya Thongdumhyu/Shutterstock.com

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8A Types of organic reactions



How can ethene gas be converted into an organic cleaner?

Organic **reaction pathways** are used in the production of a wide range of household items, from plastics and solvents to medicines and cosmetics. These pathways can be generalised in terms of the mechanism involved in converting bonds and functional groups. In this lesson, we will classify types of organic reactions and their pathways.

8A 8B

4.1.5.1 Substitution reactions (Pg 361)
4.1.5.2 Addition reactions (Pg 363)
4.1.5.3 & 4.1.5.4 Esterification reactions & hydrolysis reactions (Pg 365)
4.1.5.5 Oxidation of alcohols (Pg 366)
4.1.5.6 Reaction pathways (Pg 368)
4.1.5.7 Transesterification reactions (Pg 369)
4.1.5.8 & 4.1.5.9 Condensation reactions of biomolecules & hydrolytic reactions of biomolecules (Pg 370)

ESSENTIAL PRIOR KNOWLEDGE

1B Biodiesel
1C Food as a fuel
See questions 66–67.

STUDY DESIGN DOT POINT

- organic reactions and pathways, including equations, reactants, products, reaction conditions, and catalysts (specific enzymes not required):
  - synthesis of primary haloalkanes and primary alcohols by substitution
  - addition reactions of alkenes
  - the esterification between an alcohol and a carboxylic acid
  - hydrolysis of esters
  - pathways for the synthesis of primary amines and carboxylic acids
  - transesterification of plant triglycerides using alcohols to produce biodiesel
  - hydrolytic reactions of proteins, carbohydrates and fats and oils to break down large biomolecules in food to produce smaller molecules
  - condensation reactions to synthesise large biologically important molecules for storage as proteins, starch, glycogen and lipids (fats and oils)

KEY TERMS AND DEFINITIONS

2-Amino acid (α-amino acid) amino acid in which a carboxyl (—COOH) and an amino group ($—NH_2$) are both bonded to the second carbon atom
Addition reaction reaction where one molecule combines with another to form a larger molecule with no other products
Carbohydrate any polymer made up of sugar monomers like glucose
Condensation reaction chemical reaction in which two or more molecules combine and release a water molecule
Enzymes proteins which catalyse chemical reactions in living systems
Esterification reaction chemical reaction between organic compounds that forms at least one ester and water as products
Fats lipid molecules that are solid at room temperature
Fatty acid carboxylic acid with a long aliphatic hydrocarbon chain
Glycogen polymer made of α-glucose used by animals to store energy
Glycosidic linkage ether (—COC—) linkage that joins two sugar molecules
Hydrolysis chemical reaction in which water reacts with a larger molecule to break it into two or more smaller molecules
Lipid broad category of biomolecule commonly found in food which has two main types: fats and oils
Metabolism chemical reactions in the body's cells that change food into energy
Monosaccharide smallest building block of carbohydrates consisting of only one sugar molecule, e.g. glucose, fructose, or galactose
Oils lipid molecules that are liquid at room temperature
Polysaccharide complex carbohydrate formed from the condensation of multiple monosaccharides that are joined together by glycosidic linkages
Protein a type of biopolymer which is essential for cell and whole organism function
Reaction pathway one or more chemical reactions designed to convert reactants into a desired product
Starch polymer made of α-glucose used as an energy source by animals
Substitution reaction chemical reaction where an atom, or group of atoms in a compound, is replaced by another atom, or group of atoms
Transesterification reaction a type of chemical reaction used to produce biodiesel and glycerol

Substitution reactions 4.1.5.1

A **substitution reaction** occurs when an atom or group replaces another atom or group, resulting in the formation of a new substance.

What does a substitution reaction between alkanes and halogens look like?

Saturated hydrocarbons (alkanes) can undergo substitution reactions with halogens like chlorine and bromine to form a mixture of haloalkanes. These reactions require ultraviolet light (UV) or heat to initiate the reaction by breaking the bonds between the diatomic halogen, such as in the substitution reaction of ethane and bromine as shown in figure 1. This is also a redox reaction as bromine is reduced ($0 \rightarrow -1$) and the carbon is oxidised ($-3 \rightarrow -2.5$).

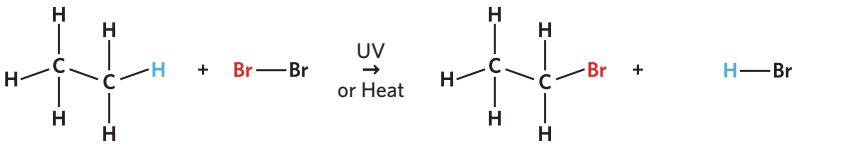


Figure 1 A possible substitution reaction involving ethane and bromine to form bromoethane

The reaction can continue to proceed with another hydrogen atom being substituted with a bromine atom to form 1,2-dibromoethane. This polysubstitution process can continue until all hydrogen atoms have been substituted.[1]

MISCONCEPTION

'Ethane and bromine exposed to UV light can be used to make pure bromoethane.'

*Polysubstitution occurs in the presence of UV, which results in a mixture of many other different bromine-containing compounds.

KEEN TO INVESTIGATE?

[1] **What is photochlorination?** Search YouTube: The Reaction between Methane and Chlorine

What does a substitution reaction between primary haloalkanes and an alkali look like?

A primary haloalkane can undergo a further substitution reaction with water in the presence of sodium hydroxide to form an alcohol (figure 2).

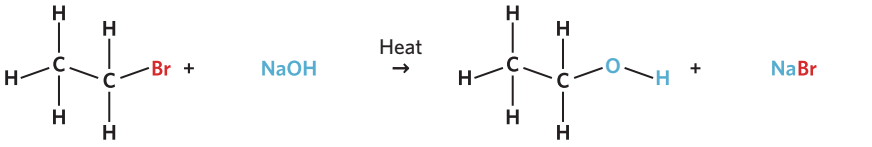


Figure 2 Substitution reaction between bromoethane and sodium hydroxide to produce ethanol

What does a substitution reaction between primary haloalkanes and water look like?

Another method, albeit a very slow reaction, is the substitution reaction of a haloalkane with water (figure 3).

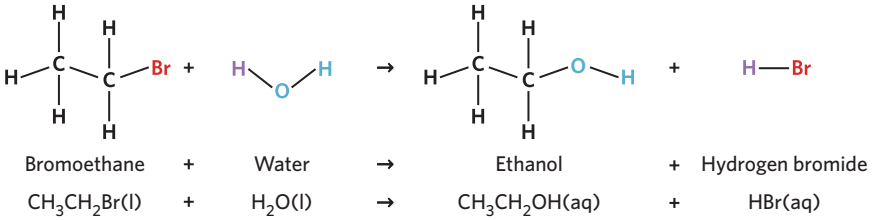


Figure 3 A very slow reaction occurs between a haloalkane and water (even when heated).

What does a substitution reaction between primary haloalkanes and ammonia look like?

Similarly, primary haloalkanes can react with concentrated ammonia in ethanol to form primary amines. As shown in figure 4, bromoethane can react with ammonia to form ethanamine (ethylamine) in two stages. The bromoethane is first heated under pressure with a concentrated solution of ammonia in ethanol to form the salt ethylammonium bromide, and then the ammonia removes a hydrogen ion from the ethylammonium ion to leave the primary amine: ethanamine.

Stage 1:

Bromoethane	+	Ammonia	→	Ethylammonium bromide salt
$CH_3CH_2Br(g)$	+	$NH_3(g)$	→	$CH_3CH_2NH_3^+Br^-(g)$

Stage 2:

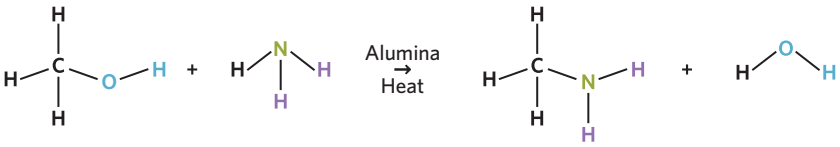
Ethylammonium bromide salt	+	Ammonia	⇌	Ethanamine	+	Ammonium bromide salt
$CH_3CH_2NH_3^+Br^-(g)$	+	$NH_3(g)$	⇌	$CH_3CH_2NH_2(g)$	+	$NH_4Br(g)$

Figure 4 Primary amines can be synthesised in a two-stage process from haloalkanes.

As the reaction in stage 2 is a reversible reaction, the more ammonia there is in the mixture, the more the forward reaction is favoured.

What does a substitution reaction between primary alcohols and ammonia look like?

Primary amines can also be formed by adding ammonia to a primary alcohol, using alumina (Al_2O_3) as a catalyst, and adding heat to the system to form a primary amine and water (figure 5).



Methanol	+	Ammonia	→	Methanamine	+	Water
$CH_3OH(g)$	+	$NH_3(g)$	→	$CH_3NH_2(g)$	+	$H_2O(g)$

Figure 5 Primary amines can be synthesised from primary alcohols.

PROGRESS QUESTIONS

Question 1

Which of the following equations shows the combined equation for the two stages involved in the formation of ethanamine?

A. $CH_3CH_2Cl(g) + NH_3(g) \rightarrow CH_3CH_2NH_3Cl(g)$

B. $2CH_3CH_2Cl(g) + 2NH_3(g) \rightarrow 2CH_3CH_2NH_3Cl(g)$

C. $CH_3CH_2NH_3Cl(g) + NH_3(g) \rightarrow CH_3CH_2NH_2(g) + NH_4Cl(g)$

D. $CH_3CH_2Cl(g) + 2NH_3(g) \rightarrow CH_3CH_2NH_2(g) + NH_4Cl(g)$

Question 2

Haloalkanes can be used as a reactant to synthesise

A. amines only.

B. alcohols only.

C. both amines and alcohols.

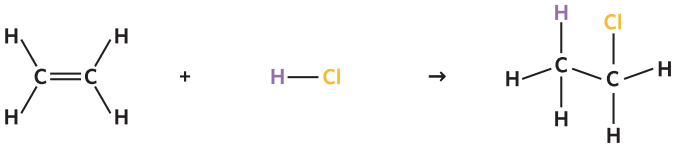
D. both alkanes and amines.

Addition reactions 4.1.5.2

In organic chemistry, an **addition reaction** is essentially an organic reaction where two or more molecules combine to form a larger molecule.

What do addition reactions between alkenes and various different molecules look like?

In addition reactions, the carbon-carbon double bonds in alkenes are broken to allow the molecule to add other atoms or groups. This results in the formation of a single product (figure 6).



Ethene	+	Hydrogen chloride	→	Chloroethane
$CH_2CH_2(g)$	+	HCl(g)	→	$CH_3CH_2Cl(g)$

Figure 6 Addition reaction between ethene and hydrogen chloride

We can use this concept to produce many other types of organic compounds. Table 1 highlights other addition reactions that relate to the study design.

USEFUL TIP

As shown in figure 6, when atoms or groups of atoms are added to the double bond, they will spread out onto both carbon atoms.

USEFUL TIP

Alkynes have a triple carbon–carbon (−C≡C−) bond and can also undergo addition reactions (no longer required knowledge in VCE chemistry).

Table 1 Examples of addition reactions to alkenes

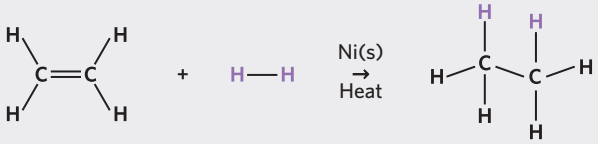
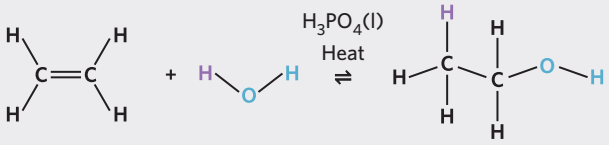
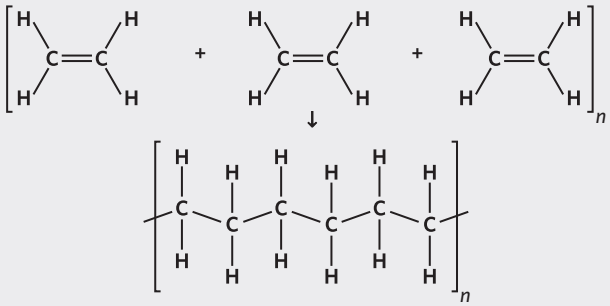
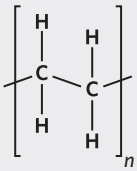
Type of addition reaction	Example	Description
Hydrogenation	 Ethene + Hydrogen → Ethane $CH_2CH_2(g) + H_2(g) \rightarrow CH_3CH_3(g)$	Alkenes can undergo addition reactions with hydrogen to produce an alkane. This reaction requires the help of a metal catalyst like nickel. This is also an example of a redox reaction as the hydrogen is oxidised ($0 \rightarrow +1$) and the carbon is reduced ($-2 \rightarrow -3$).
Halogenation		Alkenes can undergo addition reactions with halogens to produce a (di)haloalkane. This reaction does not occur (as shown) with fluorine gas as it causes an explosion to form carbon and hydrogen fluoride. This is also an example of a redox reaction as the chlorine is reduced ($0 \rightarrow -1$) and the carbon is oxidised ($-2 \rightarrow -1$).
Hydration (in particular, production of alcohols)	 Ethene + Water vapour ⇌ Ethanol $CH_2CH_2(g) + H_2O(g) \rightleftharpoons CH_3CH_2OH(aq)$	Alkenes can undergo addition reactions with water vapour to produce an alcohol. This reaction requires concentrated phosphoric acid as a catalyst, as well as heat and high pressure. When atoms are added to the double bond, they spread out and are not both added to the same carbon. **Continues →**

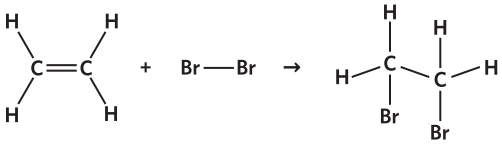
Table 1 Examples of addition reactions to alkenes

Type of addition reaction	Example	Description
Polymerisation		Alkene monomers can undergo addition reactions to form a large polymer molecule. Each monomer is usually represented as the repeated unit as seen in the polymer chain. For the example reaction involving ethene, the monomer would be represented as: 

The carbon-carbon double bond is considered a functional group due to its reactivity (an electron-rich environment) and ability to undergo addition reactions. This property is utilised as a qualitative test for unsaturation and is covered in lesson 9A.

PROGRESS QUESTIONS

Question 3



The reaction above is an example of a(n)

A. addition reaction.

B. subtraction reaction.

C. substitution reaction.

D. elimination reaction.

Question 4

Which of the following organic compounds cannot be made by a single-step addition reaction with an alkene?

A. Butanol

B. Polyethene

C. Iodoethane

D. Methanamine

Question 5

What is the name of the product formed when chlorine, Cl_2, reacts with but-1-ene?

A. 1,2-dichlorobutane

B. 1,4-dichlorobutane

C. 2,2-dichlorobutane

D. 2,3-dichlorobutane

VCAA 2015 exam Multiple choice Q13

Esterification reactions & hydrolysis reactions 4.1.5.3 & 4.1.5.4

An **esterification reaction** is a particular type of **condensation reaction** where a carboxylic acid and an alcohol react to produce a water molecule and an ester.

What does an esterification (condensation) reaction between carboxylic acids and a primary alcohol look like?

When a carboxylic acid and an alcohol combine, an ester and a water molecule are produced in a process known as esterification. Figure 7 shows an example of an esterification reaction between an alcohol and a carboxylic acid. The hydrogen atom of the hydroxyl group in propan-1-ol combines with the hydroxyl group from ethanoic acid to form water, which is eliminated from the reaction. The remaining part of the alcohol and the carboxylic acid are bonded to each other to form the ester propyl ethanoate. This process also involves the use of concentrated sulphuric acid, $H_2SO_4(l)$, which acts as a catalyst for the reaction.

USEFUL TIP

Highly concentrated solutions (for example, of sulfuric acid) can be written as 'conc. H_2SO_4' or '$H_2SO_4(l)$'. '$H_2SO_4(aq)$' is not accepted if a high concentration is essential.

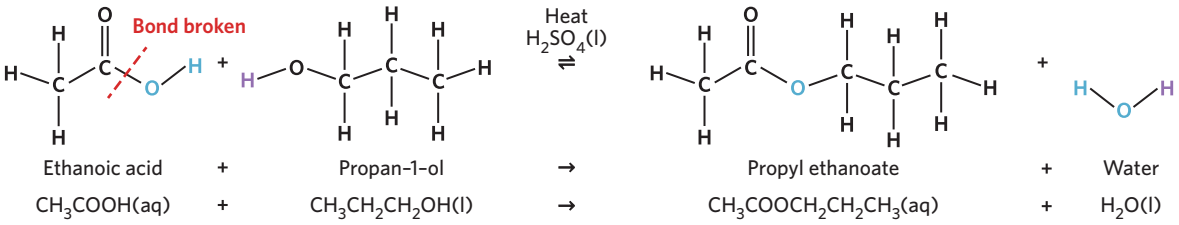


Figure 7 Esterification reaction to produce propyl ethanoate and water

What does a hydrolysis reaction of an ester look like?

Unlike condensation reactions where water is a product, in **hydrolysis**, water is a reactant and is used to break the bonds in a molecule to produce new compounds. These reactions are enabled by using an excess of dilute acid and heat, as the reactions would not occur at SLC.

The single carbon-oxygen bond in the ester group is broken during the reaction, resulting in the formation of methanoic acid and ethanol (figure 8).

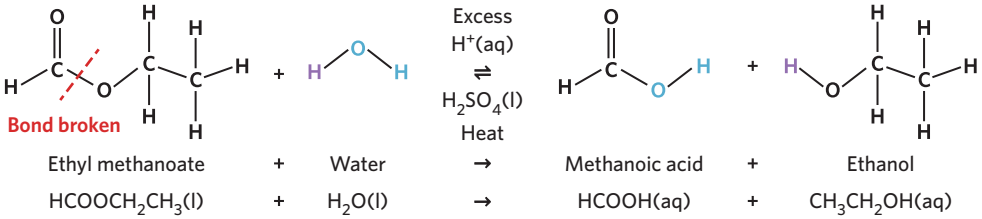


Figure 8 Hydrolysis of ethyl methanoate in excess dilute acid

USEFUL TIP

As esterification reactions are reversible, to ensure that hydrolysis is as complete as possible, an excess of water is used (which comes from the dilute acid). Conversely, when we wish to ensure that condensation is as complete as possible, minimal water is used (hence the use of concentrated acid).

PROGRESS QUESTIONS

Question 6

Esterification reactions can be considered to be a subset of which type of reaction?

A. Hydrolysis
B. Condensation
C. Polymerisation
D. Substitution

Question 7

The equation is an example of what type of reaction?

$$HCOOH(aq) + CH_3OH(l) \xrightarrow{H^+} HCOOCH_3(aq) + H_2O(l)$$

A. Condensation
B. Denaturation
C. Hydrolysis
D. Addition

Adapted from VCAA (NHT) 2018 exam Multiple choice Q2

Question 8

To prepare the ester propyl methanoate, which reagents are used?

A. Propanoic acid and methanol
B. Propanoic acid and ethanol
C. Methanoic acid and propan-1-ol
D. Methanoic acid and propan-2-ol

Oxidation of alcohols 4.1.5.5

USEFUL TIP

[O] is commonly used in equations to represent oxidising agents like $MnO_4^-(aq)$, $Cr_2O_7^{2-}(aq)$, and $H_2O_2(aq)$. These oxidising agents must be acidified.

The oxidation of alcohols is an important organic reaction as it allows ketones, aldehydes, and carboxylic acids to be produced. As mentioned in lesson 7A, there are three different types of alcohol: primary, secondary, and tertiary. Primary alcohols are predominantly used to produce carboxylic acids (and aldehydes), whereas secondary alcohols are often used to produce ketones. This lesson will focus on the oxidation of primary alcohols only.

How can carboxylic acids be synthesised from primary alcohols?

In primary alcohols, the hydroxyl (−OH) group is bonded to a carbon that is attached to only one alkyl group. Primary alcohols are first oxidised to aldehydes (+ water) and then further to carboxylic acids. Figure 9 shows an example of the processes involved in the complete oxidation of methanol to methanoic acid.

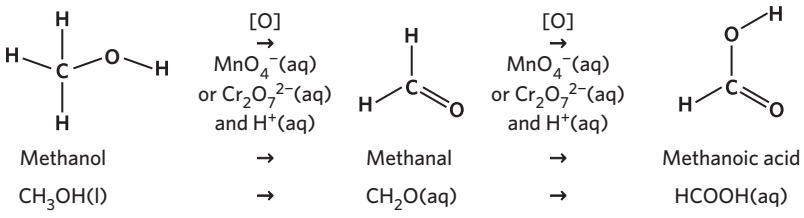


Figure 9 Complete oxidation of methanol to methanoic acid via methanal

There are a few steps that a chemist can take to maximise the production of the aldehyde instead of allowing the carboxylic acid to form. These include:

- Limit the heat (temperature) of the reaction.
- Limit the oxidising agent available in the reaction.
- Remove the aldehyde as it is being produced by distillation.

Many oxidising agents change colour during a reaction. Law enforcement agencies can use this property to determine whether a driver has been drinking alcohol or not, using a form of qualitative testing where a colour change indicates the presence of ethanol in the driver's breath.[2]

Another method that can be used to quickly oxidise primary alcohols to carboxylic acids involves the vapour form of the alcohol undergoing an oxidation reaction with oxygen from the air in the presence of a silver-based catalyst at very high temperatures. A very slow and cheap way of making carboxylic acids is allowing the primary alcohol (e.g. ethanol in wine) to be exposed to oxygen from the air (e.g. oxidise into ethanoic acid (vinegar)).[3]

KEEN TO INVESTIGATE?

[2] **How are oxidising agents used in breath testing drivers?**
Search: Breath tests using oxidising agents

KEEN TO INVESTIGATE?

[3] **What is the chemistry of different vinegars?**
Search: The sour science of vinegar varieties

USEFUL TIP

When secondary alcohols are oxidised, they produce ketones due to the location of the hydroxyl group. Tertiary alcohols do not readily oxidise.

PROGRESS QUESTIONS

Question 9

The process involved in producing a carboxylic acid from an alcohol is referred to as

A. substitution.
B. oxidation.
C. reduction.
D. polymerisation.

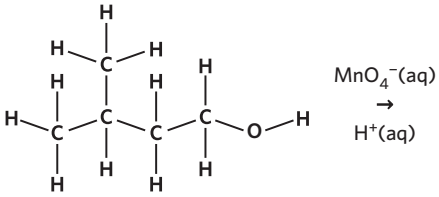
Question 10

In order for oxidising agents to function they must

A. be acidified or in alkali.
B. be a neutral solution.
C. change colour when oxidised.
D. contain a transition metal ion.

Question 11

What is the systematic name for the product of the reaction?



A. 2-methylpentanoic acid
B. 4-methylpentanoic acid
C. 2-methylbutanoic acid
D. 3-methylbutanoic acid

Adapted from VCAA 2014 exam Multiple choice Q19

Reaction pathways 4.1.5.6

Chemists often develop compounds that have properties they think will be useful for a particular purpose, e.g. for a new medicine or nano-material. Once they have come up with this compound, they need to design a way to create it from readily available materials. To do this, they compose reaction pathways to synthesise a desired organic compound by utilising known reactions (figure 10).

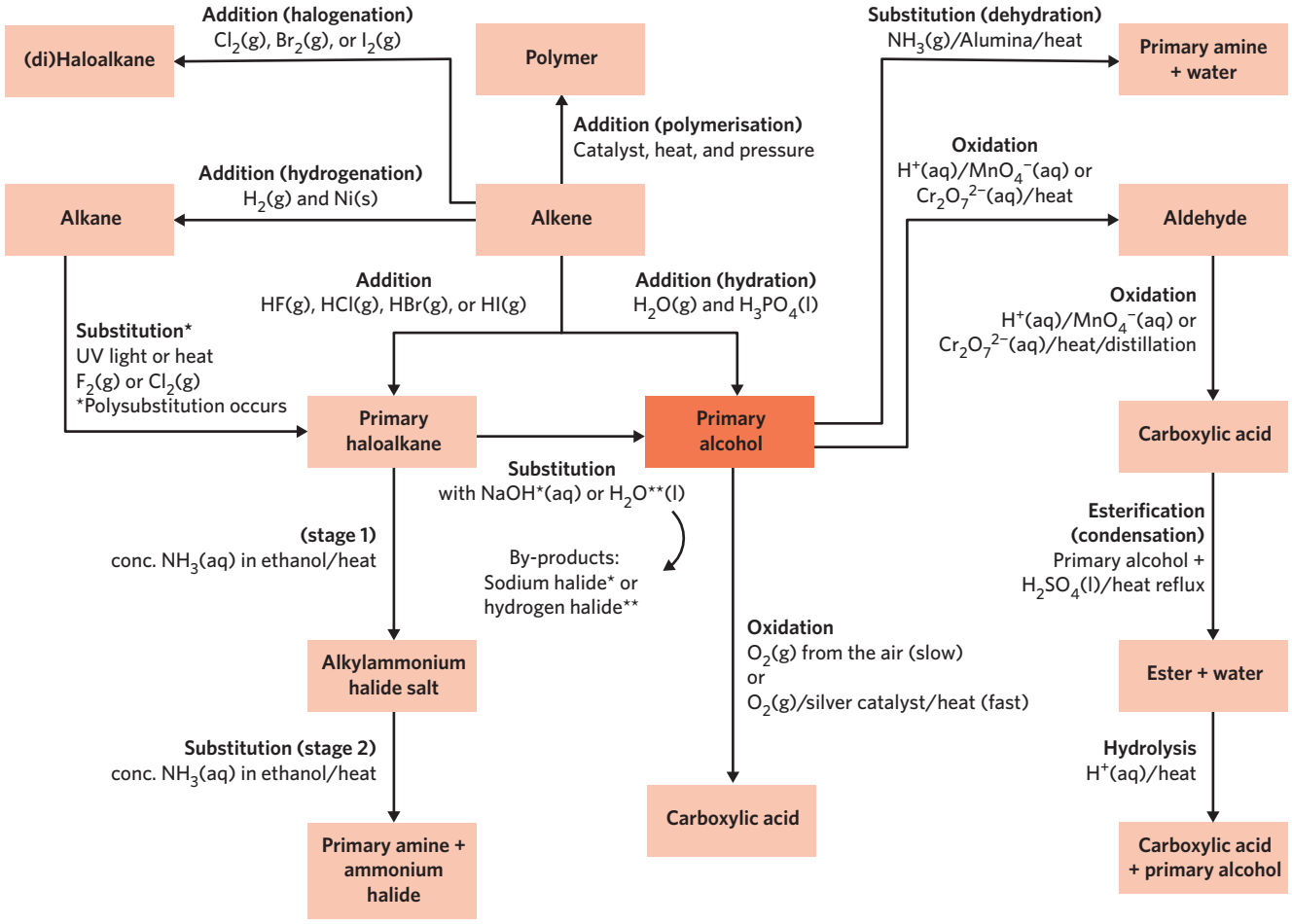


Figure 10 Possible reaction pathways in VCE chemistry

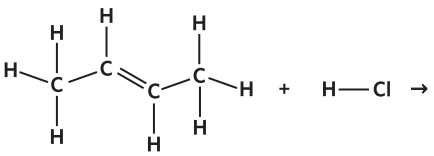
USEFUL TIP

Alkanes and alkenes are derived from crude oil, and many of them are very combustible.

PROGRESS QUESTIONS

Question 12

The systematic IUPAC name for the product of the chemical reaction is



A. 1-chlorobutane.
B. 2-chlorobutane.
C. 3-chlorobutane.
D. 4-chlorobutane.

VCAA 2013 exam Multiple choice Q10

Continues →

Question 13

What is a possible pathway that could convert propene into propanoic acid?

A. Addition then oxidation

B. Substitution then oxidation

C. Addition then substitution

D. Substitution then addition

Transesterification reactions 4.1.5.7

In lesson 1B, the reaction of triglycerides and methanol (in alkaline conditions) was introduced. In this lesson, we will take a closer look at these important reaction pathways.

How does the ester bond change?

When these triglycerides are reacted with an alcohol (methanol) in the presence of a strong alkali catalyst ($OH^-(aq)$), the original backbone is broken, a methyl group is added onto the single-bonded oxygen, and glycerol is formed as a by-product. This transforms the ester bond and separates the **fatty acid** chains, turning them into methyl esters. This process is a **transesterification reaction** (figure 11).

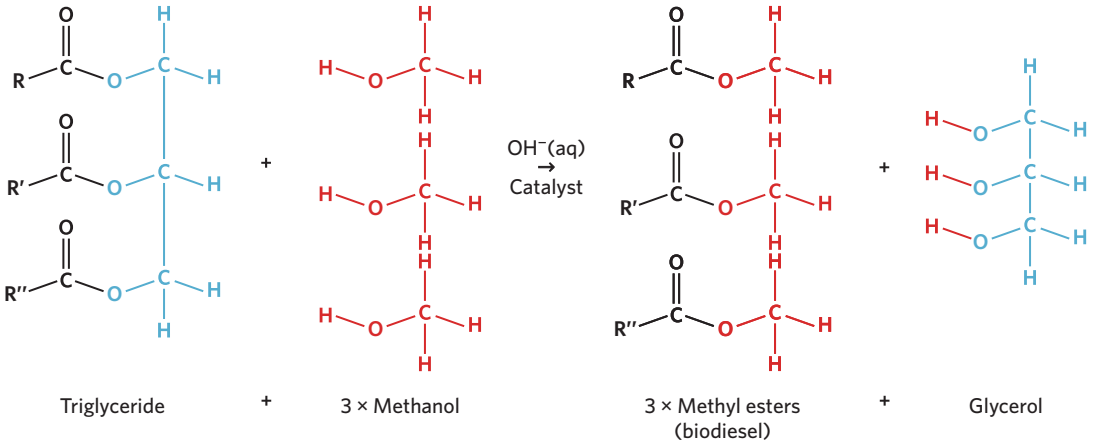


Figure 11 Transesterification of plant-based triglycerides

This type of transesterification occurs when the ester bond is transformed around the three carbonyl groups of the triglycerides. These fatty acid methyl esters make up biodiesel, and can be used as a more sustainable alternative to diesel obtained from fossil fuels.

PROGRESS QUESTIONS

Question 14

Which of the following is **not** correct regarding the process required to produce biodiesel?

A. Biodiesel is a mixture of fatty acid methyl esters.

B. Glycerol is separated from the biodiesel.

C. Biodiesel is a triglyceride.

D. The catalyst is alkaline.

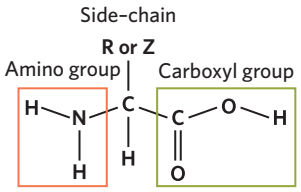


Figure 12 General structure of an amino acid

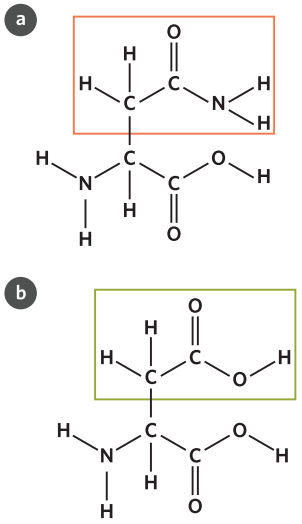


Figure 13 Structures showing the side chains of **(a)** asparagine and **(b)** aspartic acid

USEFUL TIP

If n = the number of amino acids used to form a polypeptide, the number of water molecules produced = the number of peptide links formed = $n - 1$.

Condensation reactions of biomolecules & hydrolytic reactions of biomolecules

4.1.5.8 & 4.1.5.9

Proteins are made up of monomers called amino acids. We can imagine amino acids as the small blocks used to build a big three-dimensional structure (protein). In this lesson, we will only concentrate on the **2-amino acid** (also known as α-amino acids).

What are proteins made up of?

There are 20 common 2-amino acids, all with slightly different structures. However, they all have the general structure shown in figure 12. Amino acids are required by the body for the synthesis of proteins and other important nitrogen-containing compounds.

A 2-amino acid has one amino group ($-NH_2$), one carboxyl group ($-COOH$), one side chain R, and one H atom bonded to a central carbon. The amino group and the carboxyl group are separated by the central carbon. The only difference in structure between different 2-amino acids is the R side chain.

Figure 13 shows asparagine and aspartic acid and their two different R side chains highlighted in different colours.

How does a condensation reaction synthesise proteins?

Proteins (also called polypeptides) are the products of condensation reactions occurring in the body between 2-amino acids.

A polypeptide is formed from a condensation reaction between multiple (more than two) amino acids. As illustrated in figure 14, the COOH groups react with the NH_2 groups to form multiple amide or peptide links (CONH). It is important to note that the number of water molecules produced is equal to the number of amide links formed. The different structures of proteins are covered in lesson 11B.

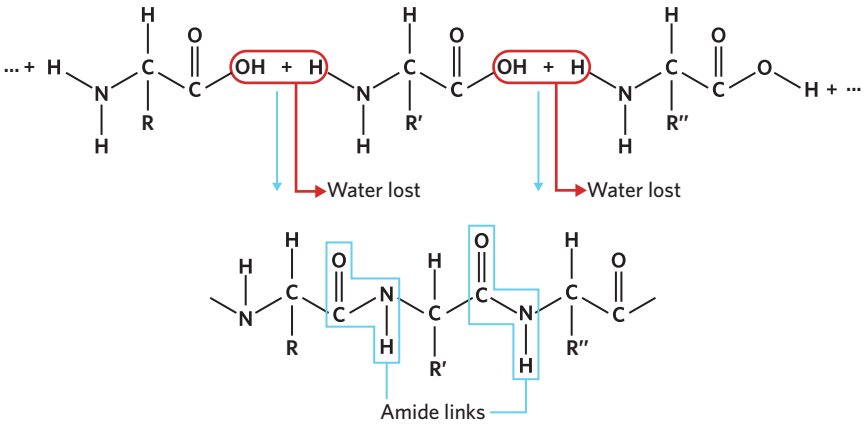


Figure 14 Condensation reaction between multiple amino acids to form a polypeptide.

How does a hydrolysis reaction break down proteins?

Proteins can be chemically digested in a process known as hydrolysis, breaking the bonds that hold its 'building blocks' (amino acids) together. Proteins are important nutrients that are broken down and digested by the body to synthesise important organic molecules in a process known as **metabolism**.

The key chemical reaction that breaks down proteins is hydrolysis. The digestion of proteins requires specific **enzymes**. An example of this is pepsin, which is found in the stomach.

When proteins are hydrolysed, the carbon-nitrogen peptide bond is broken, causing the protein to be broken down into smaller compounds. As shown in figure 15, amino acids are formed when this bond is broken, and for each peptide bond that is broken, one water molecule is consumed in the reaction.

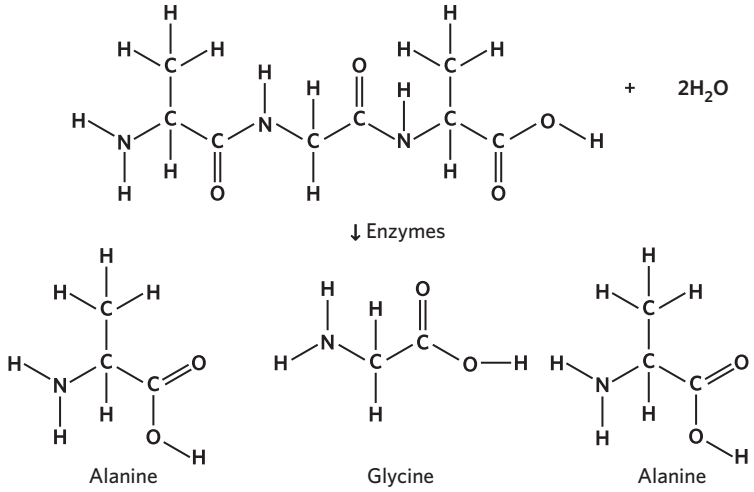


Figure 15 Hydrolysis of amide (peptide) links

How does a condensation reaction synthesise starch?

The primary building blocks of **starch**[4] (a type of **carbohydrate**) are simple 'ring sugars' known as **monosaccharides** (figure 16).

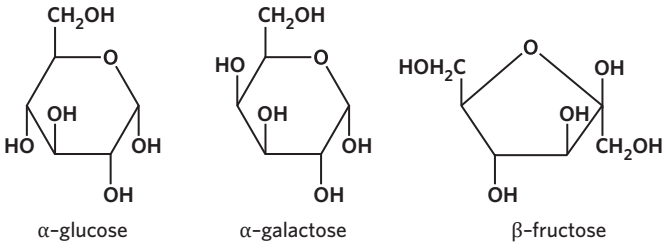


Figure 16 Structures of the common monosaccharides glucose, galactose, and fructose

Using these three simple monosaccharide rings as our basic structural units, we can increase the complexity of carbohydrates by linking two of them together by an ether link (—COC—). This ether linkage is also referred to as a **glycosidic linkage**, and is specific to the oxygen 'bridge' that forms between two ring sugars (figure 17).

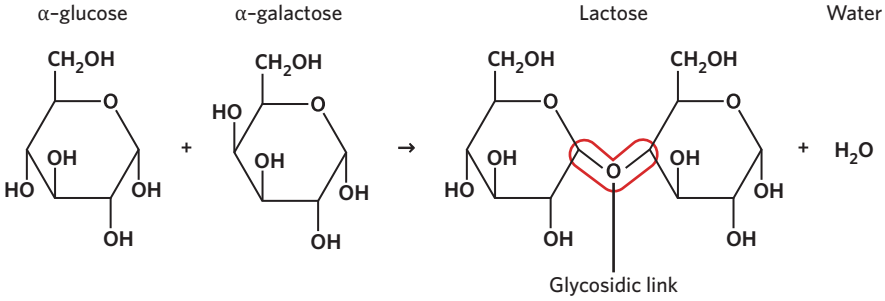


Figure 17 The formation of a carbohydrate via a condensation reaction

How does a hydrolysis reaction break down carbohydrates?

Carbohydrates, a major component of the food we eat, are broken down in the body through the process of hydrolysis. This process involves the addition of water and the presence of enzymes to convert carbohydrates into a form the human body can use for energy: monosaccharides (figure 18).

KEEN TO INVESTIGATE?

4 **Which type of starch is better for you?**
Search YouTube: Amylose vs Amylopectin | Quick Differences and Comparison

USEFUL TIP

Only polymers of α-glucose can be broken down by humans; β-glucose (cellulose) cannot.

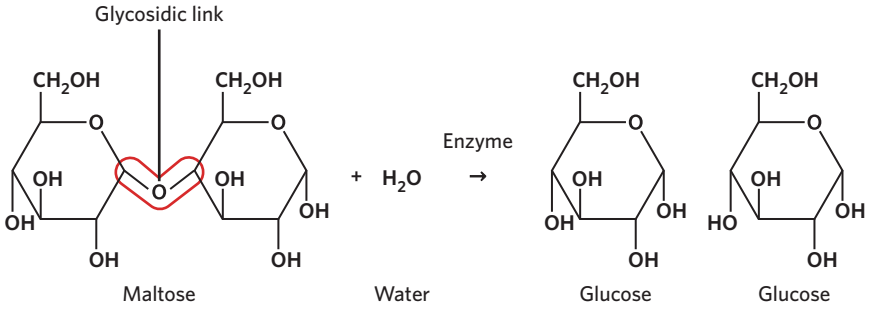


Figure 18 Breakdown of a carbohydrate into monosaccharides

This is a reaction responsible for producing glucose, our main energy source as humans (lesson 1C). Any excess glucose in the body can be stored for later use by the conversion of α-glucose into **glycogen**. Glycogen is a highly branched **polysaccharide** composed of many glucose units.

WORKED EXAMPLE 1

A condensation reaction involving 200 glucose molecules, $C_6H_{12}O_6$, produces a polysaccharide. What is the molar mass, in g mol^{-1}, of the polysaccharide?

What information is presented in the question?

The polysaccharide is made up of 200 glucose molecules joined together.

What is the question asking us to do?

Calculate the molar mass of the polysaccharide.

What strategies do we need in order to answer the question?

1. Determine the number of water molecules that would be released when making the polysaccharide.
2. Write a general equation for the sum of the molar masses of all the individual monomers.
3. Calculate the molar masses of water and glucose.

Answer

When 200 glucose molecules react to form a polysaccharide by condensation polymerisation, 199 water molecules are released.

$M(\text{polysaccharide}) = (200 \times M(C_6H_{12}O_6)) - (199 \times M(H_2O))$

$M(\text{polysaccharide}) = (200 \times 180.0 \text{ g mol}^{-1}) - (199 \times 18.0 \text{ mol}^{-1})$

$M(\text{polysaccharide}) = 32\,418 \text{ g mol}^{-1}$

VCAA 2016 exam Multiple choice Q12

How does a condensation reaction synthesise lipids (fats and oils)?

Fats and **oils** are two common types of triglycerides with different physical and chemical properties. **Lipids** are commonly found in meat, fish, butter, seeds, and some vegetables. Similar to carbohydrates, lipids provide energy to the body. However, lipids contain more than double the energy content of carbohydrates per gram.

Triglycerides are fats (solid) or oils (liquid) formed in plants when three long chain fatty acids react with glycerol. Glycerol helps create the backbone of the triglyceride molecule linking the three fatty acids (figure 19).

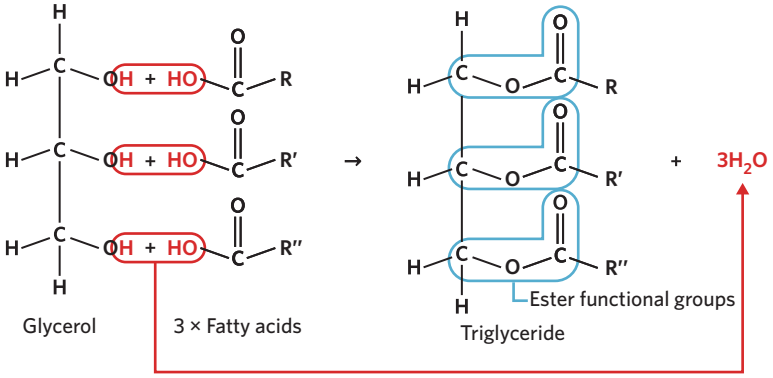


Figure 19 Condensation reaction to form a triglyceride and water

How does a hydrolysis reaction break down lipids?

Triglycerides (fats) are broken down by the process of hydrolysis in the presence of enzymes, so that the body can obtain energy from the food we eat (figure 20).

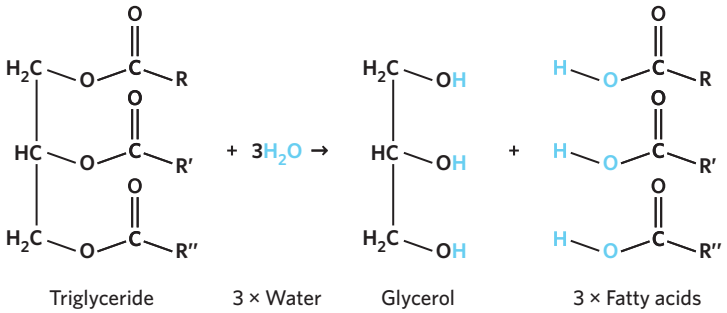


Figure 20 Hydrolysis of triglycerides to form glycerol and fatty acids

The fatty acids that are produced are then oxidised to produce carbon dioxide and water, as shown in the chemical equation representing the oxidation of palmitic acid.

$$C_{16}H_{32}O_2(aq) + 23O_2(g) \rightarrow 16CO_2(g) + 16H_2O(l)$$

When we eat more fat than our body requires, excess triglycerides are stored in adipose tissue. This tissue is found under the skin and around muscles or organs, serving as a long-term energy reserve.

PROGRESS QUESTIONS

Question 15

Which statement correctly applies to triglycerides?

A. Water is produced when they are broken down.

B. Their hydrolysis involves enzymes.

C. They are reduced to produce energy.

D. They are stored as glucose when in excess.

Question 16

What functional group is formed in the reaction of 3 fatty acid molecules and glycerol?

A. Carboxyl

B. Hydroxyl

C. Alkyl

D. Ester

Continues →

Question 17

Which two functional groups react to form an ether (glycosidic) link in starch?

A. NH_2 and OH

B. NH_2 and NH_2

C. COOH and NH_2

D. COOH and OH

Theory summary

- Substitution reactions:
  - alkane + halogen gas $\xrightarrow{\text{UV light or heat}}$ variety of haloalkanes due to polysubstitution
  - primary haloalkane + sodium hydroxide → primary alcohol + sodium halide
  - primary haloalkane + water → primary alcohol + hydrogen halide (very slow)
  - primary haloalkane + ammonia $\xrightarrow{\text{conc. } NH_3 \text{ in ethanol/heat}}$ primary amine + ammonium halide (occurs in two stages)
  - primary alcohol + ammonia $\xrightarrow{\text{Alumina/heat}}$ primary amine + water
- Addition reactions:
  - alkene + hydrogen $\xrightarrow{\text{Ni catalyst}}$ alkane
  - alkene + hydrogen halide → primary haloalkane
  - alkene + halogen → (di)haloalkane
  - alkene monomer $\xrightarrow{\text{Heat/pressure/catalyst}}$ polymer
  - alkene + water vapour $\xrightarrow{\text{conc. } H_3PO_4/\text{Heat}}$ primary alcohol
- Esterification and hydrolysis reactions:
  - primary alcohol + carboxylic acid $\xrightarrow{\text{conc. } H_2SO_4/\text{Heat}}$ ester + water
  - ester + water $\xrightarrow{\text{dilute } H^+/\text{Heat}}$ primary alcohol + carboxylic acid
- Oxidation reactions:
  - primary alcohol $\xrightarrow[MnO_4^-(aq) \text{ or } Cr_2O_7^{2-}(aq) \text{ and } H^+(aq)]{[O]}$ aldehyde $\xrightarrow[MnO_4^-(aq) \text{ or } Cr_2O_7^{2-}(aq) \text{ and } H^+(aq)]{[O]}$ carboxylic acid
  - alkane/alkene + excess oxygen $\xrightarrow{\text{Ignition source}}$ carbon dioxide + water
- Transesterification reaction:
  - triglyceride + 3 × methanol $\xrightarrow{OH^-}$ 3 × methyl ester + glycerol
- Condensation and hydrolysis reactions of biomolecules respectively:
  - amino acid + amino acid + amino acid... → polypeptide + water
  - polypeptide + water $\xrightarrow{\text{Enzymes}}$ amino acids
- When biomolecules are being synthesised, water is always a product (condensation), whereas when biomolecules are being broken down, water is a reactant (hydrolysis).
- Glucose can be stored as glycogen and then oxidised in cells to release energy.
- Proteins from food are broken down in the body (hydrolysis) and also synthesised (condensation) in the body.
- Triglycerides can be stored in adipose tissue, then oxidised in muscles to release energy.

8A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 18–20.

A reaction pathway is designed for the synthesis of the compound that has the semi-structural formula $CH_3COOCH_2CH_2CH_3$. The table gives a list of available organic reactants and reagents.

Number	Available organic reactants and reagents
I.	Acidified $KMnO_4(aq)$
II.	conc. $H_2SO_4(l)$
III.	$H_2O(g)$ and conc. $H_3PO_4(l)$
IV.	Propene
V.	C_2H_4
VI.	C_3H_7OH
VII.	C_2H_5OH

Question 18 (1 MARK)

What is the systematic name given to $CH_3COOCH_2CH_2CH_3$?

A. Ethyl propanoate

B. Propyl ethanoate

C. Butyl methanoate

D. Methyl butanoate

Question 19 (1 MARK)

Acidified potassium permanganate acts as

A. an oxidising agent.

B. a reducing agent.

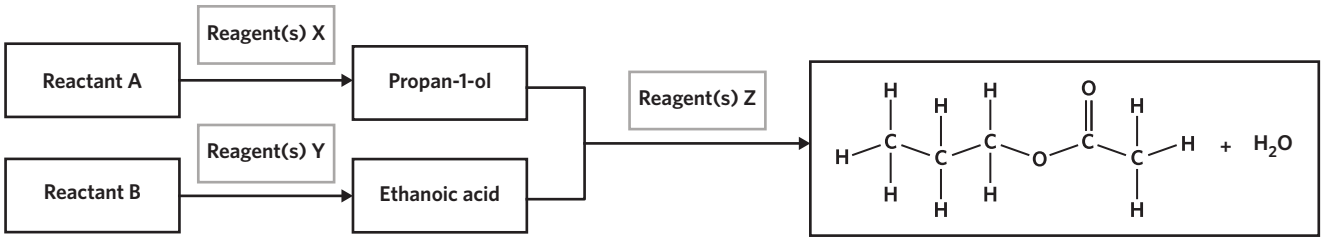
C. a spectator ion.

D. a reactant.

Question 20 (5 MARKS)

Complete the reaction pathway design flow chart.

Write the corresponding number (IV to VII) for the structural formula of of the organic reactants that belong in each of the boxes provided. Additionally, write the corresponding number (I to III) for the formula of other necessary reagents, as shown in the boxes above the arrows.



Adapted from VCAA 2015 exam Short answer Q5a

Exam-style

Question 21 (1 MARK)

Identify the option that correctly completes the following sentences.

Triglycerides are _____ by plants. Following this, the triglycerides are then broken down by the _____ lipase via hydrolysis into fatty _____ and _____. The products are then absorbed into the _____ to be transported to cells or stored in the adipose tissue.

A. broken down, endopeptidase, oils, glycerol, fat

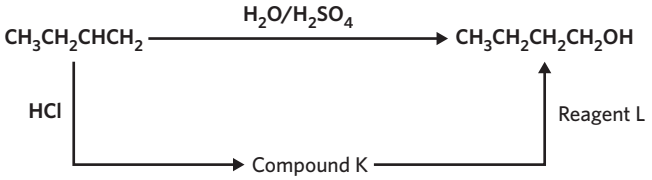
B. hydrolysed, endopeptidase, oils, glycogen, fat

C. produced, enzyme, acids, glycerol, bloodstream

D. oxidised, enzyme, acids, glucose, bloodstream

Question 22 (1 MARK)

Based on the pathways shown, which of the following correctly identifies Compound K and Reagent L respectively when $CH_3CH_2CH_2CH_2OH$ is produced?



A. Compound K: 2-chlorobutane; Reagent L: H_2O

B. Compound K: 2-chlorobutane; Reagent L: MnO_4^-

C. Compound K: 1-chlorobutane; Reagent L: H_2O

D. Compound K: 1-chlorobutane; Reagent L: MnO_4^-

VCAA (NHT) 2019 exam Multiple choice Q22

Question 23 (1 MARK)

The semi-structural formula of the product formed from the addition reaction between but-1-ene and iodine, I_2, is

A. $CH_2ICHICH_2CH_3$

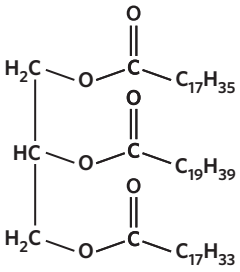
B. $CH_3CHICHICH_3$

C. $CH_3CI_2CH_2CH_3$

D. $CH_2ICH_2CH_2CH_2I$

Question 24 (1 MARK)

A triglyceride is shown.



Which one of the following statements about the triglyceride is **not** correct?

A. Glycerol was a reactant used to create the triglyceride.

B. The triglyceride will hydrolyse to carbon dioxide and water.

C. Adding the triglyceride to an alcohol in alkaline conditions is a transesterification reaction.

D. The triglyceride can be used as a reactant to make methyl esters (biodiesel).

Adapted from VCAA 2021 exam Multiple choice Q8

Question 25 (3 MARKS)

A commercial chocolate spread is commonly used in sandwiches and desserts. This food contains high amounts of proteins, triglycerides, and carbohydrates (sugars). Proteins are an important part of food, and are broken down into smaller molecules during digestion.

a. Proteins can be hydrolysed to produce alpha (α-) amino acids. Identify one structural feature common to all alpha (α-) amino acids. 1 MARK

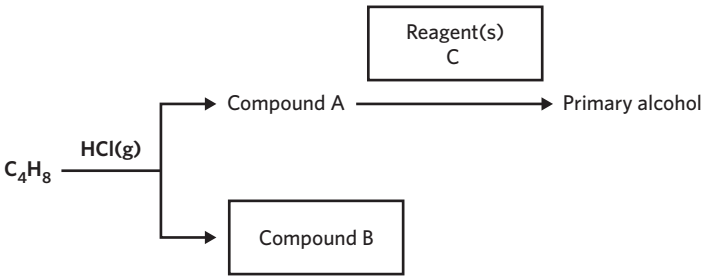
b. What is the process by which amino acids are obtained from the chocolate spread? 1 MARK

c. Identify the type of chemical reaction in which amino acids are predominantly used to synthesise proteins in the body. 1 MARK

VCAA 2019 exam Short answer Q1a,b

Question 26 (7 MARKS)

A reaction pathway that produces a primary alcohol is shown.



C_4H_8 reacts with HCl(g) to form two unbranched isomers – Compound A and Compound B.
Only Compound A can react to produce a primary alcohol.

a. Identify the type of reaction that converts C_4H_8 into Compound A. 1 MARK

b. Write the semi-structural formula for Compound B. 1 MARK

c. State the Reagent(s) C required to convert Compound A into a primary alcohol. 1 MARK

d. Propan-1-ol can react with methanoic acid to produce an organic molecule.

i. Identify the catalyst for this reaction. 1 MARK

ii. Write a balanced chemical equation for the reaction. States are not required. 2 MARKS

iii. Write the systematic IUPAC name for the organic molecule produced. 1 MARK

VCAA 2022 exam Short answer Q1

Key science skills

Question 27 (10 MARKS)

Glucose is the product of hydrolysis when the carbohydrate, sucrose ($C_{12}H_{22}O_{11}$) is broken down in the body.

An experiment was carried out to investigate the rate of hydrolysis of sucrose.

Prediction

The rate of hydrolysis is directly proportional to temperature.

Method

Identical samples of a sucrose solution were both heated and agitated in test tubes submerged in thermostatically controlled water baths. Each test tube contained the same amount of a suitable enzyme and an indicator that changes from blue to reddish when glucose is present. The time taken for the colour change to occur at different temperatures was recorded.

Results

Test tube	Temperature (°C)	Time taken to change colour (s)
1 Control (no enzyme)	23	No reaction after 180
2	10	40
3	20	25
4	30	15
5	40	5
6	50	No reaction after 180

a. Write a balanced equation for the hydrolysis of sucrose. 1 MARK

b. What reagent (not a reactant) is necessary for this reaction to occur? 1 MARK

c. Identify two variables that should remain constant. 2 MARKS

d. What is the independent variable in this investigation? 1 MARK

e. Do the results support the prediction? Justify your answer with calculations. 2 MARKS

f. Write a conclusion that is consistent with collected data. 1 MARK

g. Give an example of an improvement to the methodology outlined. 1 MARK

h. Why is it important to have a control in an experiment like this? 1 MARK

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

Question 28 🌶🌶 (3 MARKS)

A student performs an experiment where the primary alcohol pentan-1-ol is oxidised in the presence of potassium dichromate ($K_2Cr_2O_7$) to initially form the aldehyde $C_5H_{10}O$.

a. If the $Cr_2O_7^{2-}$ ion is reduced to Cr^{3+}, write the half equations for the reduction and oxidation reactions that occur. 2 MARKS

b. When the student attempts this experiment, no aldehyde is formed. Instead, a carboxylic acid is produced. Aside from limiting the temperature, suggest another possible way that the student could increase the production of the aldehyde rather than the carboxylic acid. 1 MARK

FROM LESSONS 3A & 3B

Question 29 🌶🌶🌶 (6 MARKS)

Industrially, ethanol (C_2H_5OH) is made by either one of two methods.

a. One method uses a sugar such as sucrose ($C_{12}H_{22}O_{11}$) and yeast in aqueous solution.

The production of ethanol from sucrose and yeast proceeds according to the equation:

$$C_{12}H_{22}O_{11}(aq) + H_2O(l) \rightarrow 4C_2H_5OH(aq) + 4CO_2(g)$$

Determine the mass, in grams, of pure C_2H_5OH that would be produced from 1.50 kg of $C_{12}H_{22}O_{11}$ dissolved in water. $M(C_{12}H_{22}O_{11}) = 342.0\ g\ mol^{-1}$ 3 MARKS

b. The other method involves the use of ethene (C_2H_4), which is derived from crude oil. Ethanol can then be converted to ethanoic acid, according to the following process.

$$C_2H_4(g) + H_2O(g) \xrightarrow{\text{catalyst}} C_2H_5OH(g) \xrightarrow{MnO_4^-(aq)/H^+(aq)} CH_3COOH(g)$$

i. Draw the skeletal formula of ethanol. 1 MARK

ii. Identify the two types of reactions occurring in this overall reaction. 1 MARK

iii. Identify an appropriate catalyst for the first stage of this reaction. 1 MARK

FROM LESSON 2A

Back to contents

8B Sustainability of the production of chemicals



Image: Marti Bug Catcher/Shutterstock.com

How can we design packaging that dissolves safely in the ocean?

The vast majority of common polymers in society are produced from fossil fuels, particularly crude oil. Although crude oil is currently the most widely-applicable and accessible source of polymers, long-term reliance on fossil fuel-based polymers is not sustainable. In this lesson, we will learn about how chemical processes can be made 'greener' with regard to optimising their **atom economy**, using **renewable resources**, selecting catalysts, and designing safer chemicals.

STUDY DESIGN DOT POINTS

- calculations of percentage yield and atom economy of single-step or overall reaction pathways, and the advantages for society and for industry of developing chemical processes with a high atom economy
- the sustainability of the production of chemicals, with reference to the green chemistry principles of use of renewable feedstocks, catalysis and designing safer chemicals

8A → 8B

- 4.1.6.1 Efficiency of reactions
- 4.1.7.1 & 4.1.7.2 Green chemistry principles – part 3 & renewable feedstocks
- 4.1.7.1 & 4.1.7.3 Green chemistry principles – part 3 & catalysis
- 4.1.7.1 & 4.1.7.4 Green chemistry principles – part 3 & designing safer chemicals

KEY TERMS AND DEFINITIONS

Acid rain low pH rainfall, caused by waste gases from combustion containing sulfur and nitrogen oxides, which combine with atmospheric water to form acids

Actual yield measurement of the amount of product that is actually produced as a result of a chemical reaction

Algae diverse group of aquatic organisms that have the ability to conduct photosynthesis

Atom economy mass of desired products divided by mass of all reactants given as a percentage conversion

Biomass any organic material made of plant or animal matter

Bioplastic plastic produced from biomass

Circular economy continuous cycle that focuses on the optimal use and re-use of resources from the extraction of raw materials through to production of new materials, followed by the consumption and re-purposing of unused and waste materials

Feedstock raw material used for producing another product

Percentage yield efficiency of a chemical reaction that has taken place in terms of the amount of product actually produced compared to the predicted (theoretical) yield, which is given by $\frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

Seaweed a type of macroscopic algae

Theoretical yield expected amount of a product produced in a chemical reaction given the quantities and stoichiometric ratios of the reactants

Renewable resource resource capable of being replaced by natural processes within a relatively short period of time

ESSENTIAL PRIOR KNOWLEDGE

- Circular economy

1A Sustainability

1B Renewability

See questions 68–69.

Efficiency of reactions 4.1.6.1

An assumption often made in the early years of science is that all of the reactants added into a chemical reaction are consumed and result in the complete creation of products, exactly as stated by the chemical equation. Based on what we have learned so far involving the concept of equilibrium (chapter 5), we know that this is not the case. Taking this into account, we are able to further our understanding of chemical concepts to increase the efficiency of reactions.

How can understanding atom economy be used to reduce waste?

Since unwanted by-products are often formed in a reaction, not all of the atoms in the reactant species will be involved in the production of the desired product.

$CH_3CH_2OH + CH_3CH_2COOH \rightarrow CH_3CH_2COOCH_2CH_3 + H_2O$

ethanol + propanoic acid → ethyl propanoate + water

Consider the esterification reaction shown, involving ethanol and propanoic acid. The purpose of the reaction is to produce ethyl propanoate. However, water is also released as part of the reaction and is considered a by-product. As a result, we can see that not all of the atoms involved in the reaction result in the desired product. By comparing the relative atomic mass of the constituent atoms of both the reactants and desired product(s), we are able to quantitatively determine the atom economy of the reaction:

$CH_3CH_2OH + CH_3CH_2COOH \rightarrow CH_3CH_2COOCH_2CH_3 + H_2O$

ethanol + propanoic acid → ethyl propanoate + water

$M(\text{ethanol}) = 46.0 \text{ g mol}^{-1}$ $M(\text{ethyl propanoate}) = 102.0 \text{ g mol}^{-1}$

$M(\text{propanoic acid}) = 74.0 \text{ g mol}^{-1}$

Total molar mass of atoms of desired product $= 102.0 \text{ g mol}^{-1}$

Total molar mass of reactants used $= 120.0 \text{ g mol}^{-1}$

$$\%\text{ atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$$

$$\%\text{ atom economy} = \left(\frac{102.0 \text{ g mol}^{-1}}{120.0 \text{ g mol}^{-1}}\right) \times 100\%$$

$$\%\text{ atom economy} = 85.00\%$$

The concept of atom economy is useful when planning for chemical reactions; we want reactions to minimise 'waste' and maximise the desired product. This is particularly important in making chemical reactions as sustainable and environmentally friendly as possible. Calculating the **percentage yield**, which was introduced in lesson 4B, is another method that can be used to evaluate the efficiency of chemical reactions.

How do we calculate the percentage yield of chemical reactions?

Unlike the atom economy of a reaction, percentage yield is calculated based on what is produced as a result of conducting an experiment. Calculations based on balanced chemical equations using values that are not derived from an experiment show the optimal outcome of a chemical reaction. Therefore, they are theoretical values, referred to as the **theoretical yield**. We can compare the theoretical yield to the results obtained from conducting the experiment, the **actual yield** (or experimental yield), to determine the overall percentage yield of a chemical reaction. This formula can be found in the VCE Data Book.

$$\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

WORKED EXAMPLE 1

During a combustion reaction, 90.2 g of propene reacted to form 210.4 g of carbon dioxide.

$2C_3H_6(g) + 9O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g)$

Calculate the percentage yield of the combustion reaction.

What information is presented in the question?

90.2 g propene used.

210.4 g carbon dioxide produced.

What is the question asking us to do?

Find the percentage yield of the reaction.

What strategies do we need in order to answer the question?

1. Determine the theoretical yield of carbon dioxide.
2. Compare the theoretical yield to the actual yield of carbon dioxide.
3. Determine the overall percentage yield.

Answer

Theoretical yield of carbon dioxide

$$n(C_3H_6) = \frac{90.2\text{ g}}{42.0\text{ g mol}^{-1}}$$

$$n(C_3H_6) = 2.147\text{ mol}$$

$$n(C_3H_6) : n(CO_2)$$

$$2 : 6$$

$$2.147\text{ mol} : ?$$

$$n(CO_2) = \frac{2.147\text{ mol}}{2} \times 6$$

$$n(CO_2) = 6.4428\text{ mol}$$

$$m(CO_2) = 6.4428\text{ mol} \times 44.0\text{ g mol}^{-1}$$

$$m(CO_2) = 283.48\text{ g}$$

Actual yield of carbon dioxide = 210.4 g

Overall percentage yield:

$$\%\text{ yield} = \frac{210.4\text{ g}}{283.48\text{ g}} \times 100\%$$

$$\%\text{ yield} = 74.2\%$$

As shown in the worked example, often reactions do not give us 100% yield.
This can be due to factors such as:

- reactants/products being 'lost' throughout the experimental process
- equilibrium reactions, not proceeding to completion
- the rate of the reaction being too slow for the reaction to go to completion
- impurities in the initial samples of reactants
- reactants undergoing other reactions to form different products
- for multi-step processes, inefficiencies during the intermediate phases having a cumulative impact on the percentage yield of the overall reaction.

If we want to calculate the overall percentage yield of a large reaction pathway, requiring many steps, the overall percentage yield is the product of the individual percentage yields for each step in the process.

$$\%\text{ yield} = \frac{\text{actual yield for step 1}}{\text{theoretical yield for step 1}} \times \frac{\text{actual yield for step 2}}{\text{theoretical yield for step 2}} \times 100\%$$

(for all the steps in the reaction pathway)

WORKED EXAMPLE 2

A reaction pathway is given.

A → B → C → D

The percentage yield of each step is A → B : 80 %; B → C : 60%; C → D : 90%.

What is the overall percentage yield for this pathway?

What information is presented in the question?

Three reactions and the overall reaction pathway.

The percentage yield of each of the three reactions.

What is the question asking us to do?

Calculate the overall percentage yield of the reaction pathways.

What strategies do we need in order to answer the question?

1. Convert the percentages to decimals by dividing by 100%.
2. Multiply the decimals.
3. Multiply by 100% to turn this number into a percentage.

Answer

$$\left(\frac{80\%}{100\%} \times \frac{60\%}{100\%} \times \frac{90\%}{100\%}\right) \times 100\% = 43\%$$

Overall, by considering atom economy, chemists can design reactions to be more efficient and sustainable. This is important for both environmental and economic reasons, as it can reduce waste and the use of resources.

PROGRESS QUESTIONS

Question 1

What would be the total overall percentage yield of the following reaction pathway?

$$A + B \xrightarrow{80\%} C + D \xrightarrow{70\%} E + F$$

A. 56%

B. 70%

C. 75%

D. 80%

Question 2

Which one of the following reactions has the lowest percentage atom economy for the production of ethanol, C_2H_5OH?

A. $C_2H_4(aq) + H_2O(l) \rightarrow C_2H_5OH(aq)$

B. $C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$

C. $C_2H_5Cl(aq) + NaOH(aq) \rightarrow C_2H_5OH(aq) + NaCl(aq)$

D. $C_2H_5NH_2(aq) + HNO_2(aq) \rightarrow C_2H_5OH(aq) + H_2O(l) + N_2(g)$

VCAA (NHT) 2018 exam Multiple choice Q13

Green chemistry principles – part 3 & renewable feedstocks 4.1.7.1 & 4.1.7.2

By incorporating more renewable **feedstocks** into production systems, we can reduce our reliance on non-renewable sources and move closer to a **circular economy** that minimises waste and promotes the sustainable use of resources.

How can plastics be created from renewable sources?

Polylactic acid (PLA) is a polymer formed from the condensation of lactic acid monomers, as shown in figure 1.

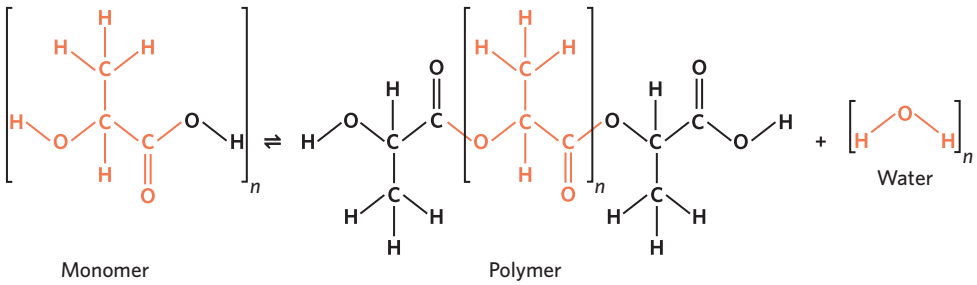


Figure 1 Lactic acid undergoes condensation polymerisation to form polylactic acid.

PLA is characterised as a **bioplastic**, as it is synthesised from naturally-occurring lactic acid, which is usually obtained via the fermentation of sugar cane or corn starch. This allows for the 'circularity' of the raw ingredients required for the synthesis of PLA.

Due to its ability to be degraded into lactic acid (a substance present in large quantities in the body), PLA is useful in 3D printers (figure 2) and the construction of medical implants, such as screws or plates to fixate broken bones. The polymer can remain intact in the body for up to 2 years during a healing process, before being broken down and naturally removed.



Image: stockphoto-graf/Shutterstock.com

Figure 2 PLA is commonly used in 3D printers.

Biodegradable polymers, such as polylactic acid (PLA) and polyhydroxy butyrate, (PHB) are made from natural and fossil resources. These biodegradable polymers could be metabolised by microorganisms and subsequently returned to nature in a short period of time. Bioplastics are purely made from bio-based resources like protein and polysaccharides, which are extracted from plants, marine organisms, or are produced by microorganisms through fermentation.

What are the different generations of biofuels?

The production and use of biofuels still raise some environmental and social concerns. The cultivation of feedstock for biofuel production may lead to deforestation, increased use of fertilisers, pesticides, and herbicides, as well as competition for land use, water resources, and agricultural products. Therefore, it is essential to develop more renewable sources and eco-friendly generations of biofuels and biofuel production methods to mitigate these concerns. Biofuels can be classified into four generations based on the renewable feedstock source and production technology (table 1).

Table 1 The different generations of biofuels

Generation	Feedstock source	Production technology	Considerations
First	Edible crops, such as corn, wheat, sugarcane, and soybean	Transesterification under alkaline conditions	• Displacement of food crops and deforestation • Competes with valuable food sources
Second	Non-food crops and waste materials, such as agricultural residues, forest residues, and household waste	Transesterification under alkaline conditions	• Lower environmental impact than first-generation biofuels • Difficult to convert **biomass** to liquid fuels
Third	**Algae** and other microbes	Can be grown in various environments, such as wastewater, saltwater, and freshwater	• High productivity and potential to absorb carbon dioxide from the atmosphere • Requires extensive processing
Fourth (emerging)	Cyanobacteria	Engineered cyanobacterial development	• Huge potential for use as a green biotechnology • Absorbs the most CO_2 and creates lipid biofuels • Currently very expensive

WORKED EXAMPLE 3

Referring to table 1, explain the advantages of using third and fourth generation biofuels over first and second generation biofuels.

What information is presented in the question?

Table 1 outlines the feedstock source and production technology and issues of the four generations of biofuel.

What is the question asking us to do?

Explain the advantages of third and fourth generation biofuels.

What strategies do we need in order to answer the question?

1. Use the information from the table only.
2. Compare advantages of third and fourth against first and second generation biofuels.

Answer

- Reduced greenhouse gas emissions:
  Third and fourth generation biofuels produce less greenhouse gas emissions compared to first and second generation biofuels.
- Reduced competition for resources:
  Third and fourth generation biofuels do not compete with the production of food crops for resources such as land, water, and fertilisers.
- Increased sustainability:
  Third and fourth generation biofuels are more sustainable as they make use of waste products, algae, and other non-food crops that are grown specifically for biofuel production.

Post-first generation biofuels offer a promising and sustainable solution to reduce carbon emissions and mitigate the impacts of climate change. However, their production and use must be carefully managed to avoid negative impacts on land use, food security, and freshwater resources.

PROGRESS QUESTIONS

Question 3

The majority of plastics currently used in society are

A. fossil fuel-based.
B. bioplastics.
C. plant-based.
D. sustainable.

Question 4

Biofuels continue to develop. The generation that is the least sustainable is the

A. first generation.
B. second generation.
C. third generation.
D. fourth generation.

Green chemistry principles – part 3 & catalysis 4.1.7.1 & 4.1.7.3

One of the most important green chemistry principles is catalysis, as it can be applied to a very broad range of processes.[1]

Nearly all industrial chemical processes involve the use of catalysts. It is therefore important to consider the environmental impact and sustainability of catalysts in their design and use.

KEEN TO INVESTIGATE?

[1] **What is green principle number 9 all about?**
Search YouTube: Green Chemistry Principle #9

Why are catalysts so important to green chemistry?

An example of how catalysts can reduce **acid rain** is the removal of sulfur from crude oil. Sulfur dioxide is the main contributor to the creation of acid rain and is largely produced from the combustion of sulfur-containing fuels (figure 3). It is therefore crucial to reduce the sulfur content of crude oil as this lessens its impact on the environment and improves its value.

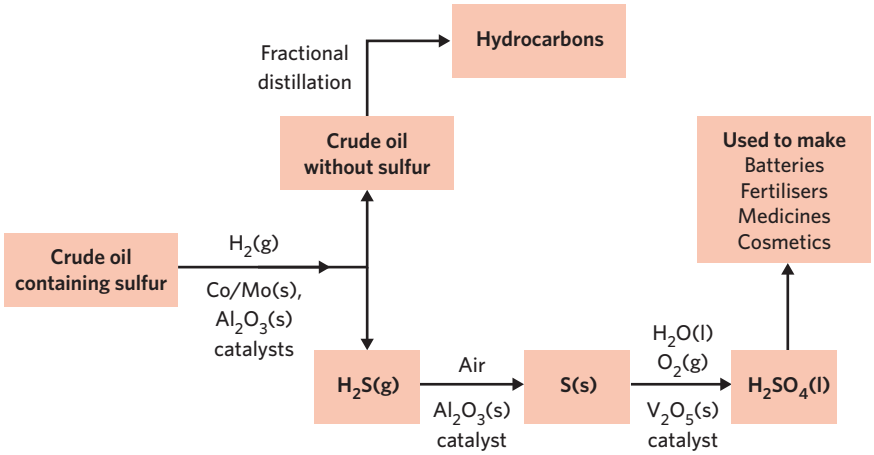


Figure 3 Outline of the catalysts involved in the desulfurisation of crude oil

The benefits of catalysis in green chemistry can be summarised as follows:

- Improved selectivity: catalysis allows reactions to occur with greater specificity, meaning that unwanted by-products are minimised or eliminated. This not only reduces waste but also saves money by improving the yield of the desired product.
- Lower energy consumption: catalysis enables reactions to occur at lower temperatures and pressures, which reduces the energy required for the reactions. This can also result in lower carbon emissions.
- Renewable source utilisation: catalysis can facilitate the use of renewable feedstocks such as biomass, which can replace fossil fuels in many applications. This reduces dependency on non-renewable resources and decreases the environmental impact of chemical production.
- Safer reactions: catalysis can enable the use of less hazardous reagents, reducing the risk of accidents and environmental contamination. This also makes chemical processes safer for workers.
- Longer catalyst lifetime: catalysts can often be reused multiple times, leading to longer catalyst lifetimes and reducing the environmental impact of catalyst production and disposal.

Overall, catalysis is a crucial tool for adhering to the principles of green chemistry. By improving efficiency, selectivity, and safety in chemical processes, catalysis can enable the development of more sustainable and environmentally-friendly solutions for a wide range of industries.

PROGRESS QUESTIONS

Question 5

Catalysts increase the rate at which products are formed. The main benefit of the use of catalysts to achieve this increase in rate is

A. a safer reaction.

B. improved yield.

C. lower energy consumption.

D. better selectivity.

Green chemistry principles – part 3 & designing safer chemicals 4.1.7.1 & 4.1.7.4

An increasing number of polymer products are marketed as **biodegradable**. However, this label may be misleading as many of these polymers take years to decompose and often leave even more harmful residue: micropolymers.

How can we design packaging to be safer in the environment?

An innovative polymer formed by condensation is polybutylene succinate (PBS), which is formed from the reaction of a carboxylic acid monomer and an alcohol monomer shown in figure 4.

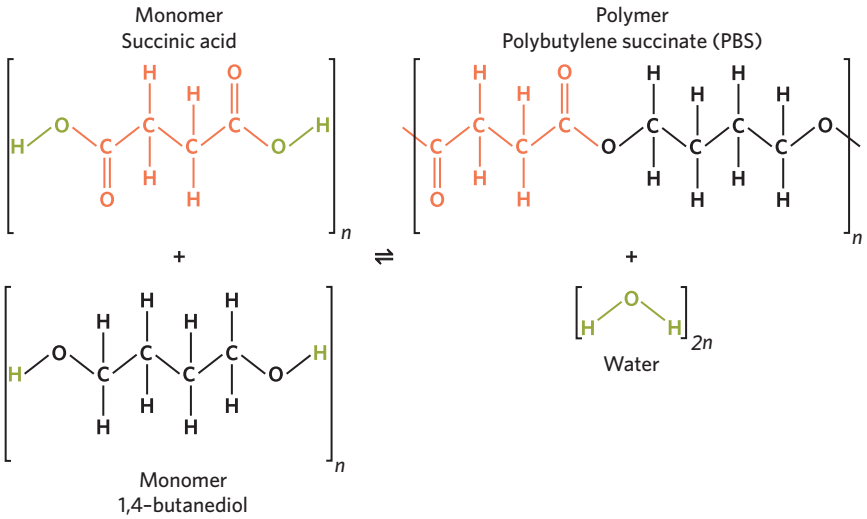


Figure 4 Succinic acid and 1,4-butanediol undergo condensation polymerisation to form polybutylene succinate (PBS).

PBS is highly biodegradable and decomposes by hydrolysis into biomass and water. It is also very flexible, and so holds great potential in a variety of packaging applications. It is non-toxic and safe for use in packaging for food and cosmetics, unlike many other polymers. Furthermore, the two reactants, succinic acid and 1,4-butanediol, are naturally-occurring and readily obtainable via the fermentation of corn or wheat.

How can seaweed be used to help improve the sustainability of food packaging?

Seaweed-derived biopolymers are gaining popularity as an alternative to traditional petroleum-based plastics in packaging materials.[2] As a renewable resource, seaweed has a number of advantages over fossil fuels including:

- lower carbon footprint
- can be grown quickly
- biodegradability (hydrolyses naturally into biomolecules)
- increased durability (improved shelf life for perishable products)
- reduced food waste
- production of oxygen by consuming carbon dioxide (deacidification of the ocean)
- can be eaten by humans (edible).

Many companies are now experimenting with seaweed-derived polymers to make a variety of packaging materials including films, coatings, and foams. Overall, the adoption of seaweed-based packaging represents a promising development in the shift towards more sustainable and environmentally-friendly packaging solutions.

KEEN TO INVESTIGATE?

[2] **How do you turn seaweed into edible packaging?**
Search YouTube:
Seaweed to Replace Plastic | Edible & Biodegradable

Seaweed-derived polymers are an example of a biopolymers, which are essentially made from biological molecules such as polysaccharides and proteins. These biopolymers are broken down easily via hydrolysis and are non-toxic in nature. Figure 5 gives examples of the safe marine sources of biopolymers that can be used in packaging.

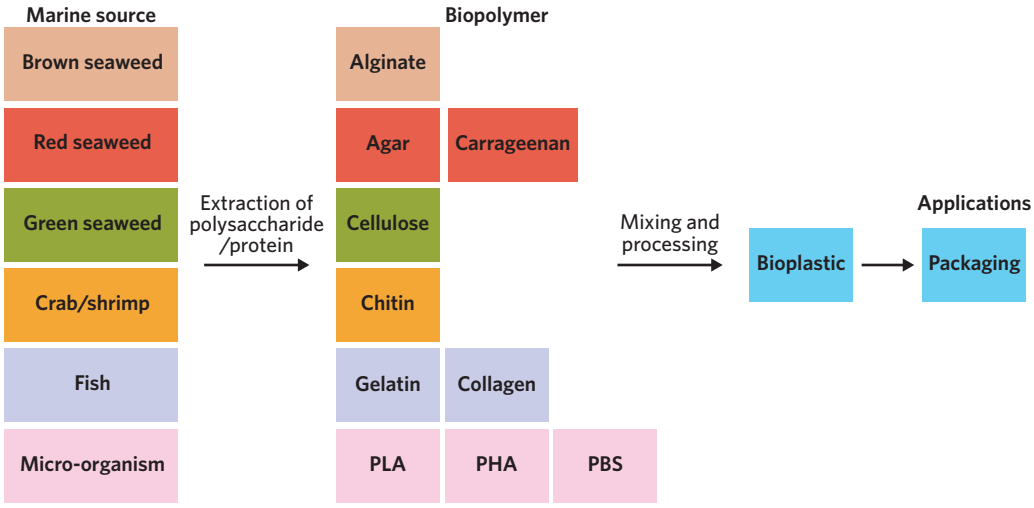


Figure 5 Marine sources of biopolymers, used for bioplastic packaging

PROGRESS QUESTIONS

Question 6

Biodegradable materials

A. are recyclable.

B. can take hundreds of years to break down.

C. always breaks down into non-toxic products.

D. are made of biopolymers that can break down into monosaccharides or amino acids.

Theory summary

- Efficiency of reactions can be determined by their atom economy:

  $$\%\ \text{atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$$

- Efficiency of reactions can be determined by their percentage yield:

  $$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

- Using renewable feedstocks in the production of chemicals moves processes closer to a circular economy that minimises waste and promotes the sustainable use of resources.
- PLA and PHB are examples of biopolymers that can be made from renewable resources.
- Conventional first generation biofuel production will soon be overtaken by more sustainable methods.
- Catalysts are one of the most important parts of green chemistry, allowing:
  - improved selectivity
  - lower energy consumption
  - renewable source utilisation
  - safer reactions.
- Biopolymers are more sustainable, safer, and less polluting than plastic packaging.
- Biopolymers can break down in the environment more easily via hydrolytic reactions.

8B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–10.

A reaction beginning with 1-bromopentane to produce pentan-1-ol is shown.

1-bromopentane + sodium hydroxide → pentan-1-ol + sodium bromide

Question 7 (1 MARK)

What are molecular formulas of 1-bromopentane and pentan-1-ol respectively?

A. C_3H_9Br and $C_3H_{12}OH$

B. $C_5H_{11}Br$ and $C_5H_{11}OH$

C. $C_3H_8Br_2$ and $C_3H_8OH_2$

D. $C_5H_{10}Br_2$ and $C_5H_{10}OH_2$

Question 8 (1 MARK)

What are the molar masses of 1-bromopentane and pentan-1-ol respectively?

A. 150.9 g mol^{-1} and 88.0 g mol^{-1}

B. 89.0 g mol^{-1} and 44.0 g mol^{-1}

C. 104.0 g mol^{-1} and 88.0 g mol^{-1}

D. 105.0 g mol^{-1} and 102.9 g mol^{-1}

Question 9 (1 MARK)

What is the molar mass of NaOH?

A. 20.0 g mol^{-1} **B.** 40.0 g mol^{-1} **C.** 80.0 g mol^{-1} **D.** 100.0 g mol^{-1}

Question 10 (1 MARK)

Calculate the atom economy in the production of pentan-1-ol from 1-bromopentane and a sodium salt.

Adapted from VCAA 2021 exam Short answer Q6bii

Exam-style

Question 11 (1 MARK)

1,2-ethanediol is the main constituent of antifreeze, used in cars. A new process has been developed to make antifreeze using renewable glycerol from biodiesel, in addition to a copper chromite. In this process, the copper chromite is most likely to be a

A. catalyst. **B.** reactant. **C.** product. **D.** condition.

Question 12 (1 MARK)

Which one of the following statements does not describe bioplastics?

A. A resource that will not be depleted within our lifetime

B. A resource that does not produce greenhouse gases when created

C. A resource derived from plants that are grown for the production materials

D. A resource that can be replaced by natural processes within a relatively short time

Question 13 (1 MARK)

Biopolymers are better for the environment, as most of them can be broken down by

A. condensation reactions. **B.** esterification reactions. **C.** hydrolysis reactions. **D.** dehydration reactions.

Question 14 (1 MARK)

A student was asked to prepare 10.5 g of calcium oxide ($M = 56.1$ g mol^{-1}) from the thermal decomposition of calcium carbonate ($M = 100.1$ g mol^{-1}). The percentage yield was 40.0%. What mass of calcium carbonate was required?

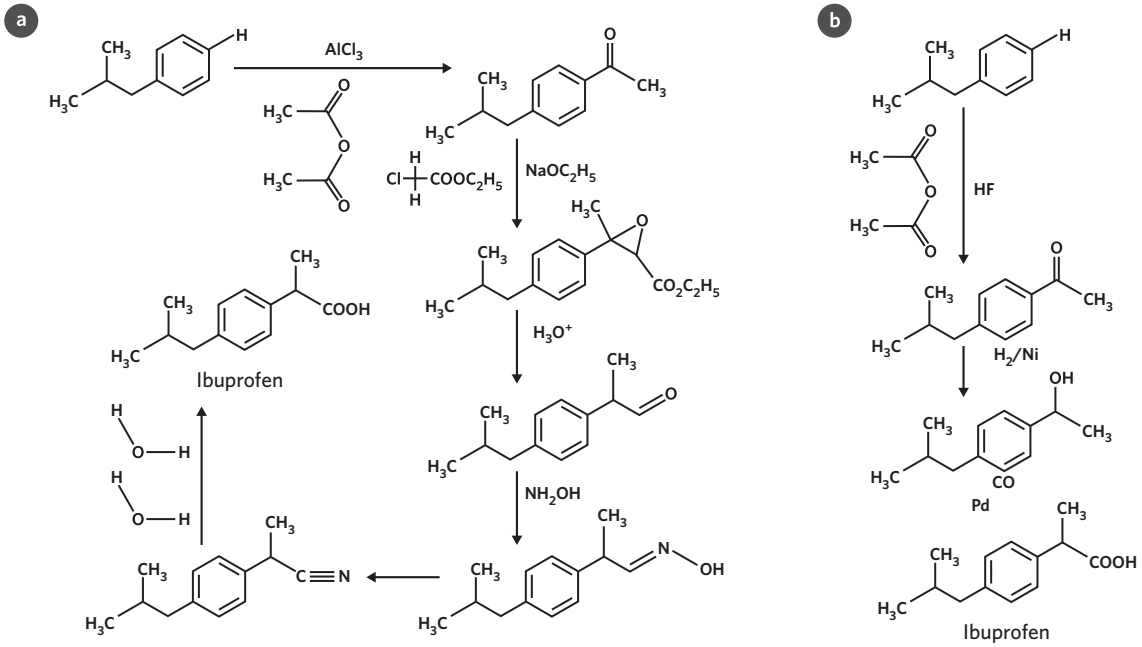
$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$

A. 10.5 g **B.** 26.25 g **C.** 46.8 g **D.** 100.1 g

Key science skills

Question 15 (8 MARKS)

Two pathways outline the (a) 1960's conventional vs (b) 1990's green synthesis used in the production of the common painkiller ibuprofen ($M = 206.29$ g mol^{-1}).



a. What is the difference between the number of steps in the two pathways? 1 MARK

b. Give two advantages other than atom economy of using the green synthesis pathways. 2 MARKS

c. The % atom economy for the synthesis of ibuprofen via the conventional synthesis pathways is 40.04%, whereas for the green synthesis pathways it is 77.44%.

i. Given that the only 'loss' in the green synthesis pathway is ethanoic acid ($M = 60.0$ g mol^{-1}), explain how the process could be made to have an atom economy of 100%. 1 MARK

ii. Using the mass of the ethanoic acid and the percentage lost, calculate the molar mass of an ibuprofen molecule. 3 MARKS

d. Comment on the accuracy of the values that you used to calculate your answer to part **c**. 1 MARK

FROM LESSON 12D

Questions from multiple lessons

Question 16 (8 MARKS)

Ethanol can be produced by either the hydration of ethene or the fermentation of glucose.

a. What is the difference, if any, in the ethanol produced by the two different methods? 1 MARK

b. Give the balanced equation (including states) for the production of ethanol using the process of fermentation. 2 MARKS

c. Which process has the greater atom economy between the hydration of ethene and fermentation of glucose? Justify your answer using appropriate calculations. 3 MARKS

d. Other than atom economy, identify two principles of green chemistry that make the production of ethanol by fermentation 'greener' than by hydration. 2 MARKS

FROM LESSONS 1B & 8A

Chapter 8 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which of the following is **not** an advantage of using catalysts to make industrial processes greener?

A. Catalysts can be reused.

B. Catalysts enable lower energy consumption.

C. Catalysts are difficult to produce.

D. Catalysts enable safer reaction conditions.

Question 2 (1 MARK)

Which of the following is considered a renewable feedstock?

A. Crude oil **B.** Biomass **C.** Coal **D.** Natural gas

Question 3 (1 MARK)

Biopolymers are safer in the environment due to their ability to readily

A. condense. **B.** react.

C. polymerise. **D.** be hydrolysed.

Question 4 (1 MARK)

Hydrolysis of an ester using heat and excess dilute sulfuric acid will produce an

A. amine and an aldehyde. **B.** amine and a carboxylic acid.

C. alcohol and a base. **D.** alcohol and a carboxylic acid.

Question 5 (1 MARK)

What is the name of the product formed when chlorine, Cl_2, reacts with pent-2-ene?

A. 1,2-dichloropentane **B.** 1,4-dichloropentane

C. 2,2-dichloropentane **D.** 2,3-dichloropentane

Question 6 (1 MARK)

When ethene is mixed with chlorine in the presence of UV light, the following reaction takes place.

$$CH_2CH_2(g) + Cl_2(g) \xrightarrow{\text{UV light}} CH_2ClCH_2Cl(l)$$

Reactions of organic compounds can be classified in a number of ways. The following list shows four possible classifications:

1. Addition
2. Substitution
3. Redox
4. Condensation

Which classification(s) applies to the reaction between ethene and chlorine?

A. 1 only **B.** 1 and 2 only

C. 1 and 3 only **D.** 4 only

VCAA 2016 exam Multiple choice Q22

Question 7 (1 MARK)

When 1.0 mol of methanoic acid, HCOOH, reacts with 2.0 mol of methanol, CH_3OH, to produce methyl methanoate, the percentage yield of the ester can be calculated by

A. $\frac{\text{Mass of ester produced}}{1.0 \text{ mol} \times 60 \text{ g mol}^{-1}} \times 100\%$

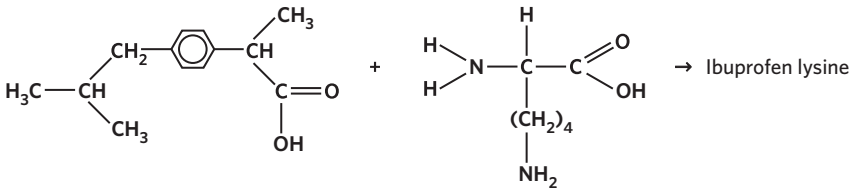
B. $\frac{\text{Mass of ester produced}}{2.0 \text{ mol} \times 60 \text{ g mol}^{-1}} \times 100\%$

C. $\frac{\text{Mass of ester produced}}{1.0 \text{ mol} \times 78 \text{ g mol}^{-1}} \times 100\%$

D. $\frac{\text{Mass of ester produced}}{2.0 \text{ mol} \times 78 \text{ g mol}^{-1}} \times 100\%$

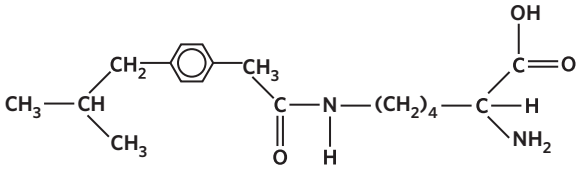
Question 8 (1 MARK)

The painkiller ibuprofen lysine is formed when ibuprofen and the amino acid, lysine, react with each other.

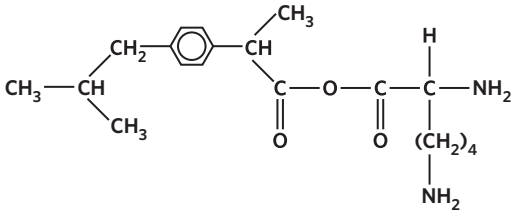


The structure of ibuprofen lysine is

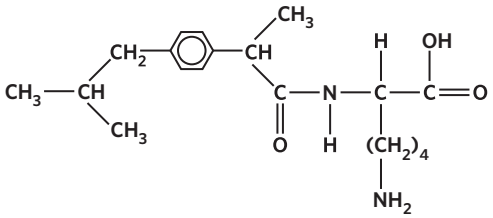
A.



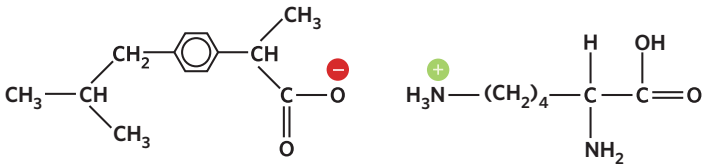
B.



C.



D.



Adapted from VCAA 2011 Exam 1 Multiple choice Q8

Question 9 (1 MARK)

Which one of the following reactions has the highest atom economy in the production of an organic molecule?

A. Complete combustion of propene, C_3H_8

B. Reaction of iodine, I_2, with propane, C_3H_8

C. Reaction of bromine, Br_2, and propene, C_3H_6

D. Formation of ethanol from bromoethane, CH_3CH_2Br, and NaOH

Adapted from VCAA 2022 exam Multiple choice Q27

Question 10 (1 MARK)

The molar mass of glycerol, $C_3H_8O_3$, is 92.0 g mol^{-1}. The production of 65.0 g of $C_3H_8O_3$ from tripalmitin, $C_{51}H_{98}O_6$, which is a triglyceride,

A. requires 12.7 g of water.

B. requires 38.2 g of water.

C. produces 12.7 g of water.

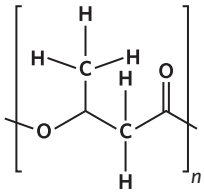
D. produces 38.2 g of water.

VCAA 2022 exam Multiple choice Q10

Short answer (30 MARKS)

Question 11 (3 MARKS)

Polyhydroxybutyrate (PHB) is a polymer formed by condensation, with the structural formula shown.



What chemical property allows this polymer to be biodegradable, and how does this property relate to the implementation of a circular economy?

Question 12 (4 MARKS)

A sample of glycogen is found to be made up of 650 glucose molecules, each having the molecular formula $C_6H_{12}O_6$ and molar mass 180.0 g mol^{-1}.

a. Write a balanced equation for the formation of this glycogen molecule from the individual glucose monomers in an aqueous solution. 1 MARK

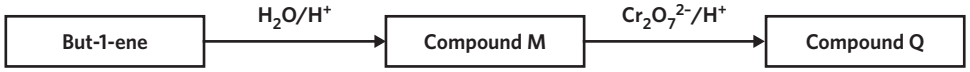
b. What is the name given to this kind of reaction? 1 MARK

c. Identify the two different possible names given to the functional group that forms between the glucose monomers. 1 MARK

d. What is the molar mass of this glycogen molecule? 1 MARK

Question 13 (8 MARKS)

The following diagram represents a reaction pathway for the synthesis of Compound Q from but-1-ene.



a. Referring to the pathway outlined:

i. Draw the skeletal formula for but-1-ene. 1 MARK

ii. Compound M forms when but-1-ene is hydrated at a high temperature in the presence of an acid catalyst. Give the IUPAC name of Compound M. 1 MARK

iii. When Compound M is reacted with acidified dichromate ions, $Cr_2O_7^{2-}$, Compound Q is formed. Draw the semi-structural formula of Compound Q. 1 MARK

b. 1-chloropropane can be reacted with ammonia to produce an uncharged organic molecule, Compound R.

i. Write the overall equation for the reaction that occurs. 1 MARK

ii. Give the IUPAC name of Compound R. 1 MARK

iii. Name the type of reaction that produces Compound R. 1 MARK

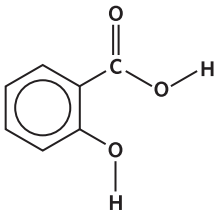
iv. Calculate the percentage atom economy for the production of Compound R. 2 MARKS

Adapted from VCAA 2019 exam Short answer Q2

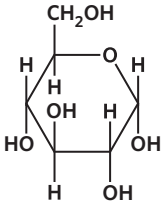
Question 14 (8 MARKS)

A number of important organic molecules are given below.

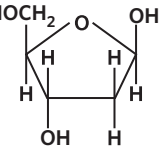
A.



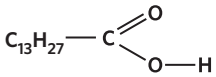
B.



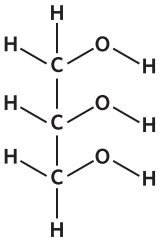
C.



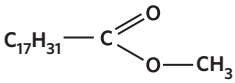
D.



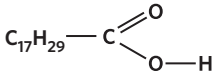
E.



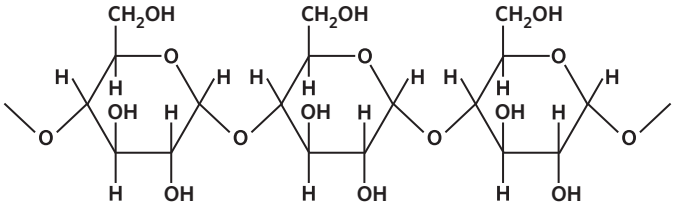
F.



G.



H.



a. In each of the following questions give the letter or letters that correspond to the compounds above. Each letter may be used once, more than once, or not at all.

i. Which molecule could be a major component in biodiesel? 1 MARK

ii. Which molecule is considered a waste product from a transesterification reaction? 1 MARK

iii. Which two molecules are produced when a triglyceride containing no carbon-carbon double bonds undergoes hydrolysis? 1 MARK

iv. Which molecule could represent starch? 1 MARK

v. Which molecules can react with themselves to form an ether link? 1 MARK

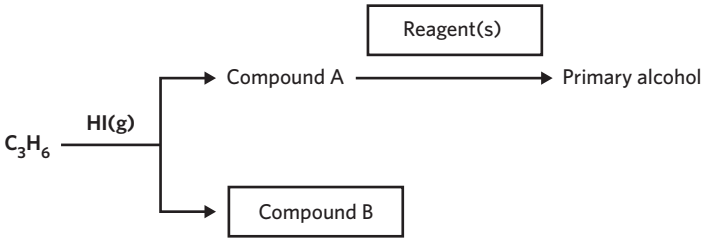
vi. Which molecule represents an unsaturated fatty acid molecule? 1 MARK

b. Name the type of reaction occurring and reagent required when molecule H is broken down in the body. 2 MARKS

Adapted from VCAA 2011 Exam 1 Short answer Q1

Question 15 (7 MARKS)

A reaction pathway to produce a primary alcohol is shown.



C_3H_6 reacts with HI(g) to form two isomers – Compound A and Compound B.

Only compound A can react to produce a primary alcohol.

a. Identify the type of reaction that converts C_3H_6 into Compound A. 1 MARK

b. Write the semi-structural formula for Compound B. 1 MARK

c. State the reagent(s) required to convert Compound A into a primary alcohol. 1 MARK

d. Methanol can react with propanoic acid to produce an organic molecule.

i. Identify the catalyst for this reaction. 1 MARK

ii. Name the type of reaction occuring. 1 MARK

iii. Write a balanced chemical equation for the reaction (states are not required), and give the systematic IUPAC name for the organic molecule produced. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q1

Key science skills (10 MARKS)

Question 16 (8 MARKS)

Rudolph Diesel tested his first engine using peanut oil, and since then, scientists have continued to improve the sustainability of the production of biofuels. Using green principles, suggest and explain four ways in which the conventional process of transesterification to produce biodiesel could be made greener. Write your answers using the following sub-headings:

a. Triglycerides 2 MARKS

b. Potassium hydroxide 2 MARKS

c. Methanol 2 MARKS

d. Glycerol 2 MARKS

FROM LESSON 12B

Question 17 (2 MARKS)

Use the information from the following tables to answer the questions.

Fossil fuel energy requirements for the petrodiesel life cycle (a non-renewable feedstock)		
Stage	**Fossil fuel energy (kJ)**	**Percentage (%)**
Crude production	1112.593	92.75
Domestic crude transport	3.235	0.27
Foreign crude transport	13.021	1.09
Crude oil refining	64.499	5.38
Diesel fuel transport	6.174	0.51
Total	1199.522	100.00

Fossil fuel energy requirements for the biodiesel life cycle (a renewable feedstock)		
Stage	**Fossil fuel energy (kJ)**	**Percentage (%)**
Soybean agriculture production	65.6	21.08
Soybean transport	3.4	1.09
Soybean crushing	79.6	25.61
Soy oil transport	7.2	2.31
Soy oil conversion	150.8	48.49
Biodiesel transport	4.4	1.41
Total	311.0	100.00

a. Quantitatively compare the total amount of energy from fossil fuels that is required over the production life cycles of petrodiesel vs biodiesel. 1 MARK

b. What is the most notable difference in energy requirements when comparing the stages of both life cycles? Use values to justify your answer. 1 MARK

FROM LESSON 12C

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UNIT 4 AOS 2

How are organic compounds analysed and used?

In this area of study students focus on laboratory and instrumental analyses of organic compounds, and the function of some organic compounds as medicines. They use distillation to separate mixtures, use volumetric analysis to calculate redox quantities, and explore how instrumental analysis is used to ensure the quality of consumer products. Students explain how some medicines that bind to the active sites of enzymes function by inhibiting the enzymes' mode of action.

The selection of learning contexts should allow students to develop practical techniques to analyse organic compounds. Students develop their skills in the use of scientific equipment and apparatus. They may perform qualitative tests to identify features of organic compounds, such as the degree of saturation in fats and oils and the identification of functional groups in an unknown compound. Students may perform quantitative analyses including redox titrations to determine concentrations and quantities of substances, such as the amount of Vitamin C in fruits. They design and improve on experiments such as the testing of the viscosity of alcohols.

They respond to challenges such as the identification of a molecule using primary data from analytical techniques used in the laboratory or secondary data obtained from spectroscopy. Students may use distillation to extract and purify the natural organic compounds in plants, such as extracting limonene from orange peel.

Outcome 2

On completion of this unit the student should be able to apply qualitative and quantitative tests to analyse organic compounds and their structural characteristics, deduce structures of organic compounds using instrumental analysis data, explain how some medicines function, and experimentally analyse how some natural medicines can be extracted and purified.

Reproduced from VCAA VCE Chemistry Study Design 2024–2027

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9

CHAPTER 9

Laboratory analysis of organic compounds

LESSONS

9A Testing for functional groups

9B Analysis of consumer products

9C Volumetric analysis using redox titrations

Chapter 9 review

KEY KNOWLEDGE

- qualitative tests for the presence of carbon-carbon double bonds, hydroxyl and carboxyl functional groups
- applications and principles of laboratory analysis techniques in verifying components and purity of consumer products, including melting point determination and distillation (simple and fractional)
- measurement of the degree of unsaturation of compounds using iodine
- volumetric analysis, including calculations of excess and limiting reactants using redox titrations (excluding back titrations)

9A Testing for functional groups

STUDY DESIGN DOT POINT

- qualitative tests for the presence of carbon-carbon double bonds, hydroxyl and carboxyl functional groups

9A 9B 9C

- 4.2.1.1 Carbon-carbon double bonds
- 4.2.1.2 Hydroxyl groups
- 4.2.1.3 Carboxyl groups

ESSENTIAL PRIOR KNOWLEDGE

7A Primary, secondary, and tertiary alcohols

7A Unsaturated

See questions 70–71.



Image: Rattiya Thongdumhyu/Shutterstock.com

How can you qualitatively identify an alcohol, carboxylic acid, or unsaturated compound?

Using a range of different chemical tests, it is possible to qualitatively identify different functional groups found in certain compounds. In this lesson, we will investigate multiple ways in which specific functional groups can be qualitatively identified.

KEY TERMS AND DEFINITIONS

Carboxyl group a combination of two functional groups (−COOH) attached to a single carbon atom, namely, hydroxyl (−OH) and carbonyl (C=O) groups

Hydroxyl group a functional group (−OH) with one hydrogen and one oxygen atom

Carbon-carbon double bonds 4.2.1.1

Compounds that contain carbon-carbon double bonds are said to be unsaturated. As mentioned in lesson 8A, a carbon-carbon double bond is electron-dense, causing it to be particularly susceptible to addition reactions.

How can compounds containing carbon-carbon double bonds be qualitatively identified?

Unsaturated organic compounds containing carbon-carbon double bonds can be qualitatively identified using two different oxidising agents: $Br_2(aq)$ and $KMnO_4(aq)$.

Bromine water test

Bromine water, $Br_2(aq)$, is commonly used as a reagent to test for unsaturation in organic compounds. It can be used to determine whether a compound contains double or triple bonds, as these unsaturated bonds react with bromine water, causing it to decolourise. The method for qualitatively testing for unsaturation using bromine water is shown in figure 1.

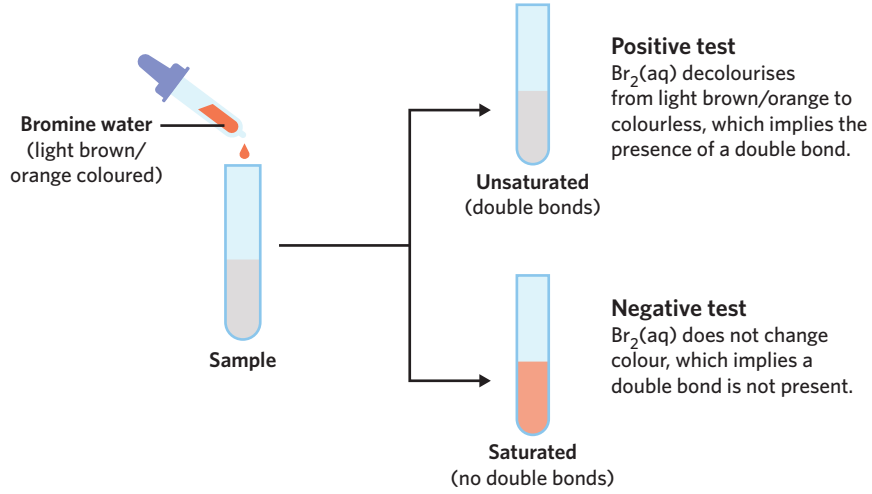


Figure 1 Test for unsaturation using bromine water

If the organic compound is unsaturated (contains double or triple bonds), it will react with the bromine water, causing it to turn from light brown/orange to colourless (figure 2a). This is due to the formation of a colourless dibromoalkane compound (figure 2b).

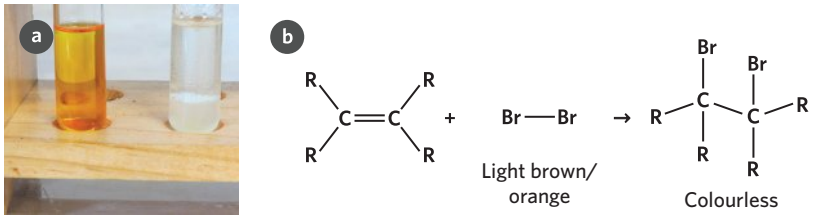


Figure 2 **(a)** The colour change and **(b)** the general equation for addition of bromine water to an alkene

It is important to note that this test is specific for unsaturation and does not provide information about the type or location of the unsaturated bonds. Additionally, some unsaturated compounds may react very slowly with bromine water (or not at all), so it is always recommended to perform additional tests or use other techniques for a more accurate characterisation of unsaturation in organic compounds.

Potassium permanganate test

Acidified potassium permanganate, $KMnO_4$(aq), is commonly used as a reagent to test for the presence of unsaturated organic compounds. The reaction between $KMnO_4$ and an unsaturated compound involves the reduction of the purple-coloured $KMnO_4$ solution to a colourless solution. Using alkaline potassium permanganate involves the reduction of the purple-coloured $KMnO_4$ solution to a dark green solution followed by a brown precipitate.

The method for qualitatively testing for unsaturation using alkaline potassium permanganate is shown in figure 3.

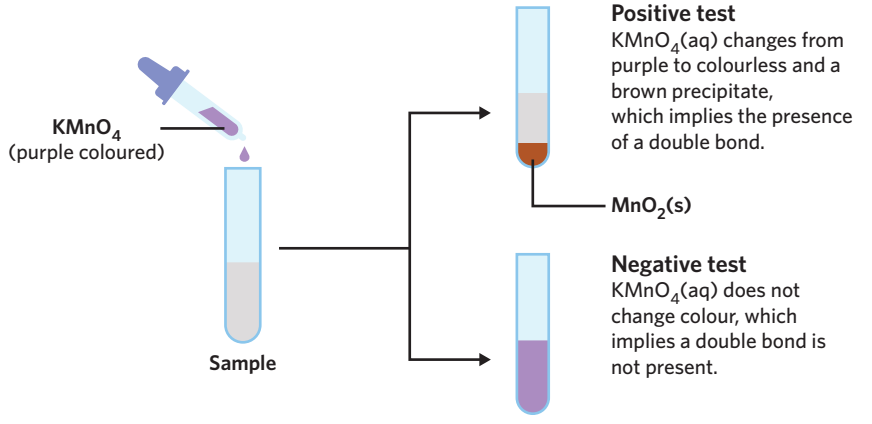


Figure 3 Testing for unsaturation using alkaline potassium permanganate

If the organic compound is unsaturated, such as an alkene or alkyne, the purple $KMnO_4$ will be gradually decolourised and/or turned into a brown precipitate. The brown precipitate formed in alkaline conditions is manganese dioxide, MnO_2 (figure 4a). This colour change indicates the organic compound is unsaturated (figure 4b).

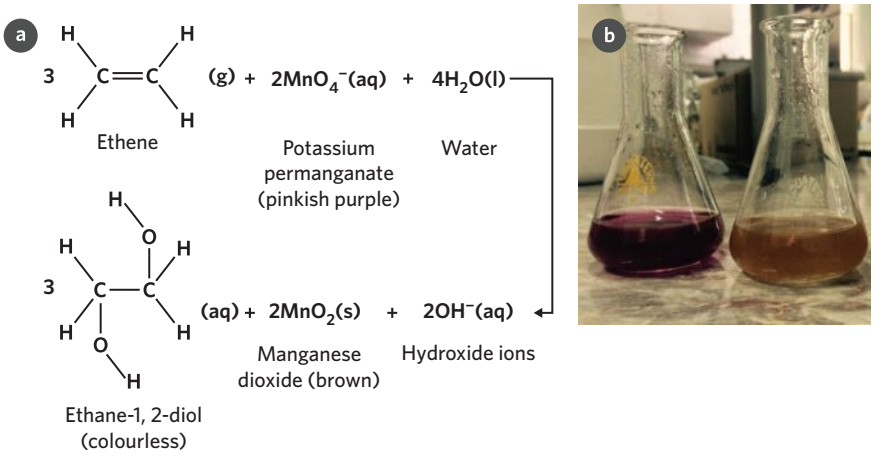


Figure 4 **(a)** The equation for addition of alkaline potassium permanganate to ethene **(b)** and the colour change

It is important to note that the test with potassium permanganate is not specific for a particular type of unsaturation. It only indicates the presence of double or triple bonds in the organic compound.

MISCONCEPTION

'Only carbon-carbon double bonds make a compound unsaturated.'

Alkynes have a carbon-carbon triple bond (−C≡C−), making them unsaturated; they react similarly to alkenes. Alkynes are no longer required in the study design.

USEFUL TIP

Potassium permanganate/dichromate can also oxidise alkenes to a ketone and/or carboxylic acid.

PROGRESS QUESTIONS

Question 1

Which of the following rows correctly describes the results of a bromine water test?

	Hydrocarbon	Observations on adding bromine water	Saturated or unsaturated?
A.	Pentene	Remains light brown/orange (no change)	Saturated
B.	Pentane	Decolourises from light brown/orange to colourless	Saturated
C.	Hexene	Decolourises from light brown/orange to colourless	Unsaturated
D.	Hexane	Remains light brown/orange (no change)	Unsaturated

Question 2

The manganese ion changes oxidation state and is responsible for the colour change.

How does the oxidation state of manganese change when $KMnO_4$ is converted into MnO_2 in the presence of an unsaturated compound?

A. Reduced from +7 to +4

B. Oxidised from +7 to +4

C. Reduced from +4 to +7

D. Oxidised from +4 to +7

Hydroxyl groups 4.2.1.2

The **hydroxyl group** (−OH) is a functional group with one hydrogen and one oxygen atom. Oxygen is very electronegative in comparison to hydrogen, resulting in this group being reactive.

How can organic compounds containing hydroxyl groups in alcohols be qualitatively identified?

Organic compounds containing hydroxyl groups can be qualitatively identified using several different methods.

Acidified potassium dichromate test

Adding acidified potassium dichromate ($K_2Cr_2O_7(aq)/H^+(aq)$) can be used to qualitatively determine whether a primary or secondary alcohol is present in a solution. When $Cr^{6+}(aq)$ ions are reduced to form $Cr^{3+}(aq)$ ions, the solution turns from orange to green (figure 5) in the presence of a primary or secondary alcohol.

$$\underset{\text{Orange}}{Cr_2O_7^{2-}(aq)} + 3CH_3CH_2OH(l) + 8H^+(aq) \rightarrow \underset{\text{Green}}{2Cr^{3+}(aq)} + 3CH_3CHO(aq) + 7H_2O(l)$$

Acidified potassium dichromate will also show a positive result with aldehydes, but not ketones.

Lucas test

The Lucas test can be used to qualitatively determine whether a primary, secondary or tertiary alcohol is present. When the suspected alcohol has been mixed with Lucas reagent (a mixture of concentrated hydrochloric acid and zinc chloride), if an alcohol is present, it will produce a cloudy liquid (figure 6).

$$\underset{\text{Colourless}}{R{-}OH(l)} + HCl(aq) \xrightarrow{ZnCl_2(s)} \underset{\text{Cloudy}}{R{-}Cl(l)} + H_2O(l)$$

Acidified potassium dichromate followed by the silver mirror test

As discussed in lesson 8A, if a very small amount of acidified potassium dichromate is added to an excess of a primary alcohol, partial oxidation occurs to produce an aldehyde. The silver mirror test (Tollens' test) involves mixing the suspected oxidised primary alcohol with Tollens' reagent (ammoniacal silver nitrate solution). If an aldehyde is present, then a reduction reaction occurs and a silver mirror-like substance is formed (figure 7).[1]

$$2Ag(NH_3)_2^+(aq) + CH_3CHO(aq) + 3OH^-(aq) \rightarrow 2Ag(s) + 4NH_3(aq) + 2H_2O(l) + CH_3COO^-(aq)$$

The silver mirror test will show a positive result with aldehydes (which are produced from the partial oxidation of primary alcohols) but not ketones (which are produced from the oxidation of secondary alcohols).



Image: Camilla Acconcia/Shutterstock.com

Figure 7 Silver atoms are deposited when an aldehyde is tested with Tollens' reagent.

USEFUL TIP

Potassium permanganate can also oxidise primary and secondary alcohols.

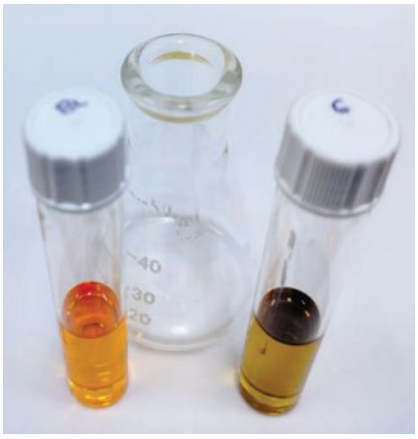


Image: Palra/Shutterstock.com

Figure 5 Using potassium dichromate a primary or secondary alcohol can be oxidised, turning from orange to green.

STRATEGY

It is normal to leave spectator ions, like potassium cations in potassium dichromate, $K^+(aq)$, out of redox equations.

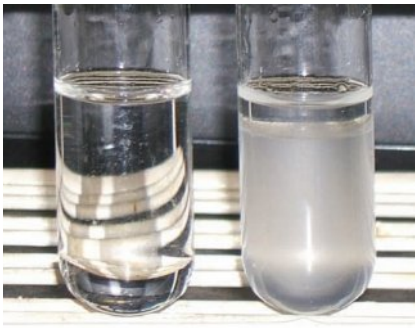


Figure 6 An alcohol can produce a cloudy precipitate.

KEEN TO INVESTIGATE?

1 **How can you make your own silver mirror?**
Search YouTube: Make Glass Mirrors with Silver Nitrate

WORKED EXAMPLE 1

To qualitatively determine the presence of a primary alcohol, which type of chemical reaction is commonly carried out?

What information is presented in the question?

Qualitatively testing for the presence of a primary or secondary alcohol.

What is the question asking us to do?

Determine the type of reaction used to test for the presence of the hydroxyl group of an alcohol.

What strategies do we need in order to answer the question?

1. Work out which tests are possible.
2. Choose the most common type of reaction involved in these tests.

Answer

The possible options are

- acidified potassium dichromate test
- lucas test
- acidified potassium dichromate and silver mirror test
- potassium permanganate test.

The acidified potassium dichromate, potassium permanganate, and silver mirror tests involve redox reactions. A redox reaction (oxidation) is commonly used to determine the presence of a primary alcohol.

PROGRESS QUESTIONS

Question 3

What type of chemical reaction occurs during the formation of the silver mirror?

A. Displacement
B. Combustion
C. Neutralisation
D. Redox

Question 4

Which of the following types of alcohol does not readily react?

A. Primary
B. Secondary
C. Tertiary
D. All of the above

Carboxyl groups 4.2.1.3

The **carboxyl group** (−COOH) is a combination of two functional groups attached to a single carbon atom, namely, hydroxyl (−OH) and carbonyl (−C=O) groups. The carboxyl group makes a compound behave as a weak carboxylic acid, which results in it being reactive with basic substances.

How can organic compounds containing carboxyl groups in acids be qualitatively identified?

Organic compounds containing carboxyl groups can be qualitatively identified using several different methods.

Acid-base indicator test

Adding an acid-base indicator, such as phenolphthalein, to the unknown compound can help in identifying the carboxyl group. The indicator changes colour from its basic form to its acidic form in the presence of carboxyl groups (figure 8). Universal or litmus paper can also be used as an alternative to test for the presence of a carboxylic acid.



Image: Rattiya Thongdumhyu/Shutterstock.com

Figure 8 Phenolphthalein changes from pink to colourless when an acid is added.

Reaction with metal carbonates or metal bicarbonates

Carboxylic acids can react with carbonates or bicarbonates to produce carbon dioxide gas, which can be observed as effervescence or bubbling (figure 9). This is a type of neutralisation reaction where the carboxylic acid reacts with a base to form a salt, water and carbon dioxide. Therefore, adding a solution of sodium carbonate (Na_2CO_3) or sodium bicarbonate ($NaHCO_3$) to the unknown compound can help identify the presence of a carboxyl group. An example of the reaction of ethanoic acid and sodium carbonate to form sodium ethanoate is shown.

$$2CH_3CH_2COOH(aq) + Na_2CO_3(s) \rightarrow 2CH_3CH_2COONa(aq) + H_2O(l) + CO_2(g)$$



Image: JPBC/Shutterstock.com

Figure 9 Carboxylic acids readily effervesce with sodium carbonate.

Esterification test

Treating the unknown compound with an alcohol and a strong acid, such as concentrated sulfuric acid, can lead to the formation of an ester. The sweet, aromatic smell of the ester can imply the presence of a carboxyl group.

It is important to note that these tests may not provide a definitive identification of the compound; they merely indicate the presence of a functional group. Additional confirmatory tests, such as spectroscopic analysis (covered in chapter 10) are required for a more accurate identification of specific compounds.

MISCONCEPTION

'Effervescence with sodium carbonate means the compound has a carboxyl group.'

All types of acids will cause bubbling e.g. HCl, H_2SO_4.

PROGRESS QUESTIONS

Question 5

Carboxyl groups are the functional group found in all

A. mineral acids.
B. carboxylic acids.
C. diprotic acids.
D. inorganic acids.

Question 6

Carboxyl groups are made up of

A. carbonic and carbonyl functional groups.
B. ester and hydroxyl functional groups.
C. hydroxyl and carbonyl functional groups.
D. ether and ester functional groups.

Question 7

Which of the following is **not** a possible qualitative test that could be used to identify an organic acid?

A. pH paper
B. Acid-base indicator
C. Aromatic aroma
D. Silver mirror test

Theory summary

- Qualitative tests for the presence of carbon-carbon double bonds (unsaturation) include bromine water (light brown/orange to colourless) and potassium permanganate (purple to colourless and/or brown).
- Qualitative tests for the presence of hydroxyl groups in primary and/or secondary alcohols include acidified potassium dichromate (orange to green), Lucas test (colourless to cloudy) and acidified potassium dichromate with the silver mirror test.
- Qualitative tests for the presence of carboxyl groups include acid-base indicator (change in colour varies), reactions with metal carbonates or metal bicarbonates (bubbling) and esterification (sweet aromatic smell).

9A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 8–10.

Qualitative tests are carried out on an organic compound. The following table summarises the results.

Test	$Na_2CO_3(aq)$	Lucas	Bromine water
Observation	No change	Colourless to cloudy	Light brown/orange to colourless

Question 8 (1 MARK)

What type of compound is the Lucas test used to identify?

A. Carboxylic acids
B. Unsaturated compounds
C. Alcohols
D. Only tertiary alcohols

Question 9 (1 MARK)

What functional group is the bromine test used to identify?

A. Hydroxyl group
B. Carboxyl group
C. Carbonyl group
D. Carbon-carbon double bond

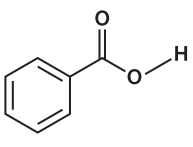
Question 10 (2 MARKS)

Determine the functional groups present in the organic compound. Explain your reasoning.

Exam-style

Question 11 (5 MARKS)

The molecule shown was investigated.



a. What tests could be carried out on the compound to confirm the presence of its functional groups? 2 MARKS

b. Give an appropriate name for the compound. 1 MARK

c. If the structure of this compound was not known, what information could your chosen tests from part **a** provide? Explain your answer. 2 MARKS

Key science skills

Question 12 🌶🌶 (5 MARKS)

A student was asked to confirm the identity of three labelled known organic compounds.

I. Cyclohexene

II. Propan-1-ol

III. Pent-3-en-oic acid (3-pentenoic acid)

a. Plan how the student could use qualitative testing to confirm the identity of the three labelled colourless solutions, referring to the functional groups involved. 3 MARKS

b. What does the student need to do to ensure that they comply with all applicable safety guidelines during the investigation? 2 MARKS

FROM LESSON 12B

Questions from multiple lessons

Question 13 🌶🌶🌶 (9 MARKS)

Primary alcohols can be oxidised to aldehydes and carboxylic acids.

a. Give the balanced equation, including state symbols, for the reaction of butan-1-ol and acidified potassium permanganate and classify this type of reaction. 3 MARKS

b. Explain why butan-1-ol is classified as a primary alcohol. 1 MARK

c. Why is it not possible to produce a carboxylic acid from butan-2-ol using acidified potassium permanganate? 1 MARK

d. Outline a reaction pathway, including all reagent(s) and condition(s), that can produce an ester using a carboxylic acid as the starting reagent. 4 MARKS

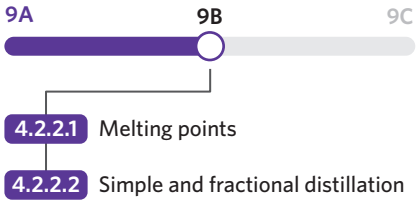
FROM LESSONS 7A & 8A

Back to contents

9B Analysis of consumer products

STUDY DESIGN DOT POINT

- applications and principles of laboratory analysis techniques in verifying components and purity of consumer products, including melting point determination and distillation (simple and fractional)



ESSENTIAL PRIOR KNOWLEDGE

- Condenser
- Forces of attraction
- Crystal lattice

See questions 72–74.



How is a condenser used to verify the components of alcoholic beverages?

Laboratory analysis techniques, including **melting point** determination and distillation, aid in verifying the quality, purity, and appropriate composition of consumer products. They provide valuable information about the identity and presence of impurities, helping manufacturers meet the required standards and regulations. In this lesson we will learn about the application and principles of three common techniques utilised for this purpose: melting point determination, **simple distillation**, and **fractional distillation**.

KEY TERMS AND DEFINITIONS

Boiling point the temperature at which the vapour pressure of a liquid equals the atmospheric pressure

Distillate a liquid product condensed from gas during distillation

Fractional distillation technique used to separate liquids (fractions) with a narrow range of boiling points

Melting point the temperature at which the two states, liquid and solid, coexist in equilibrium

Mixture a substance that can be separated into two or more substances by physical means and displays the properties of the substances that it is composed of

Pure substance a substance composed of one type of element or one type of compound that cannot be separated into two or more substances by physical means

Simple distillation technique used to separate liquids with significantly different boiling points

Vapour pressure the pressure exerted by the vapour in equilibrium with the liquid phase at a given temperature

Volatile readily converted into a gas

Melting points 4.2.2.1

The melting point of a substance is the temperature at which the two states, liquid and solid, coexist in equilibrium, or, put more simply, when the forces of attraction between molecules or ions are overcome and a change in physical state occurs from solid to liquid. This temperature is used to determine purity by comparing experimental melting points with known values.

How can the purity of a compound be determined by its melting point?

Principles

Melting point determination involves the measurement of the temperature at which a solid compound changes from a solid to a liquid state. **Pure substances** have a sharply defined melting point (within a very small temperature range of 1–2 °C), while impure substances have both a lower and broader melting temperature. The melting point of an impure compound is less (termed 'melting point depression') than a pure compound due to the impurities disrupting and weakening the overall molecular or lattice structure, meaning less energy is required to overcome the forces of attraction in the solid, thereby causing it to melt.[1] The stronger the forces between the atoms or ions in a compound, the higher the melting point will be.

USEFUL TIP

A substance's temperature remains constant during phase changes due to its particles absorbing the supplied heat energy (which prevents it from increasing further) and instead using it to overcome the attractive forces between the ions, molecules or compounds.

Applications

Melting point determination is widely used in various industries to evaluate the purity of solid consumer products. For example, it can be used to determine the purity of pharmaceutical drugs, industrial chemicals, food additives, and cosmetic ingredients.

MISCONCEPTION

'All pure compounds have a sharply defined melting point.'

Some pure compounds undergo decomposition prior to reaching their melting points and will therefore have multiple or a range of melting temperatures.

Techniques

A solid sample under investigation is first dried and then forced into a capillary tube (figure 1).

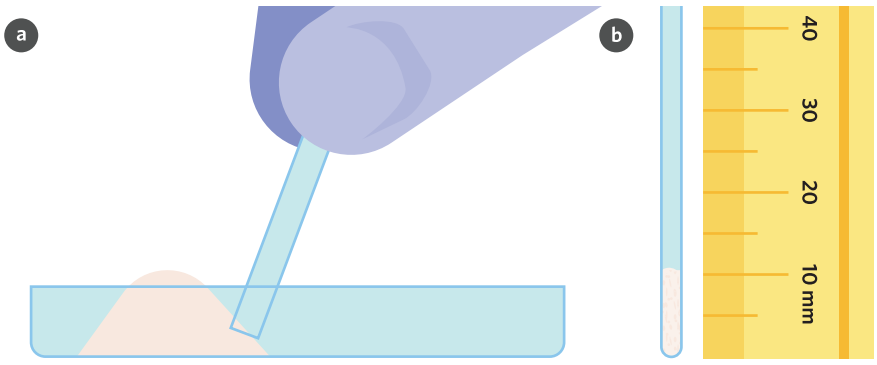


Figure 1 **(a)** Adding the sample to the open end of a capillary tube and **(b)** the amount required after flicking the capillary tube

MISCONCEPTION

'Melting involves the breaking of bonds.'

Melting is a physical change that occurs when the forces (not ionic or covalent bonds) of attraction (dispersion, permanent dipole-dipole, and hydrogen bonds) between molecules or compounds are overcome.

KEEN TO INVESTIGATE?

1 **Why is salt added onto roads in winter?**
Search: How Does Salt Melt Snow and Ice?

The capillary tube can then be placed either in a Thiele tube, metal block, or specialised electronic melting point device (figure 2).

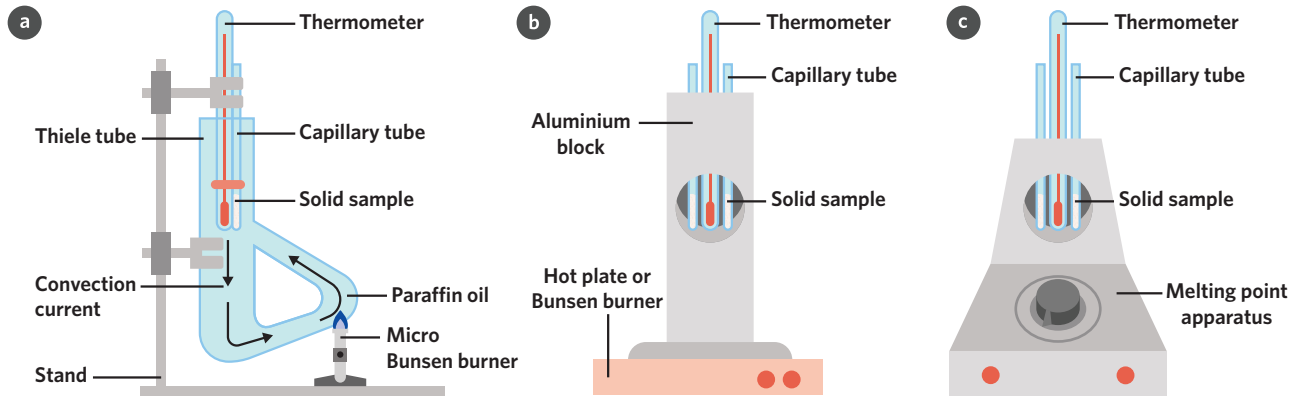


Figure 2 Different methods commonly used to determine a melting point: **(a)** Thiele tube **(b)** Metal block **(c)** Electronic device

USEFUL TIP

In the pharmacological industry, chemists define the exact melting point as the temperature at which the meniscus point (figure 3b) exists, which occurs when there is both a solid phase at the bottom and a clear liquid phase on top with a well-defined visible meniscus.

In all three of these techniques, the melting point is determined by recording the temperature at the moment just before the solid 'collapses', which is equal to the melting point of the solid (figure 3). This procedure is then repeated to obtain an average, and the experimental melting point is compared against the known melting point of a pure sample.

- If the range of melting points is lower and broader than that of the pure sample, then the compound is not pure or is a **mixture** of impure compounds.
- If the melting point is lower yet well-defined, then the unknown substance is likely a mixture of pure compounds.

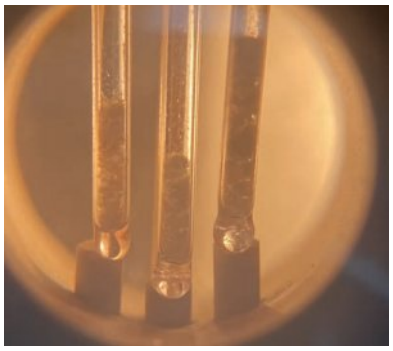


Image: Dofme/Shutterstock.com

Figure 4 Capillary tubes containing a solid sample that has yet to melt

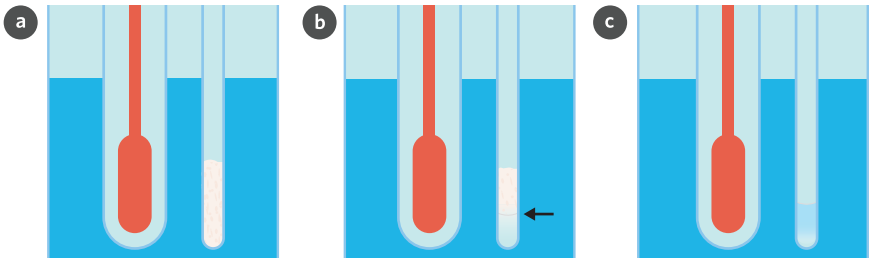


Figure 3 Stages of a **(a)** solid melting as the **(b)** meniscus appears before all the solid sample **(c)** 'collapses' to the clear point

Some melting point determination devices (figure 4) are very accurate (more than 6 significant figures) and are in fact able to verify the identity of certain compounds that have an accurately known melting point.

WORKED EXAMPLE 1

The widely used painkiller aspirin has a melting point of 135 °C.

Which melting point determination technique would allow a very controlled temperature change to occur in order to record the most accurate melting point?

What information is presented in the question?

Aspirin has a melting point of 135 °C.

What is the question asking us to do?

Identify which of the available techniques would allow the melting to be recorded the most accurately.

What strategies do we need in order to answer the question?

1. Identify the available techniques.
2. Decide which technique would allow the heating of the sample to be controlled most precisely.

Answer

The possible techniques are the use of a Thiele tube, a metal block, or a specialised electronic melting point device. Given that both a Thiele tube and a block of aluminium require the use of a Bunsen burner, they would not be as sensitive as the temperature control of an electronic melting point device. Therefore, the electric melting point device would be most suitable for accurately recording the melting point of aspirin.

PROGRESS QUESTIONS

Question 1

Melting is best described as a

A. chemical change.

B. physical change.

C. chemical reaction.

D. breaking of bonds.

Question 2

Melting point determination can be used to assess the

A. structure of the sample.

B. functional groups of the sample.

C. density of the sample.

D. purity of the sample.

Question 3

What effect do impurities have on the melting point of a compound?

A. Increase

B. Decrease

C. Increase or decrease

D. No change

Simple and fractional distillation 4.2.2.2

Distillation is a process used to separate and verify components of a liquid mixture based on their different **boiling points**. Distillation is also explored in great depth in a medicinal context in lesson 11A. Boiling point is the temperature at which the **vapour pressure** of a liquid equals the atmospheric pressure, or, put more simply, it is the temperature at which the forces of attraction between atoms or ions are overcome and a change in physical state from liquid to gas occurs. The stronger the forces between the atoms or ions in a compound, the higher the boiling point.

MISCONCEPTION

'Boiling involves the breaking of bonds.'

Boiling is a physical change that occurs when the forces (not ionic or covalent bonds) of attraction (dispersion, permanent dipole-dipole, and hydrogen bonds) between molecules or compounds are overcome.

How can the components of a mixture be verified using distillation?

Principles

Distillation relies on boiling, evaporation, and condensation to separate **volatile** components from non-volatile or less volatile ones. Simple distillation is used to separate liquids with significantly different boiling points, while fractional distillation utilises a fractionating column, which allows separation of liquids wwith similar boiling points (figure 5).

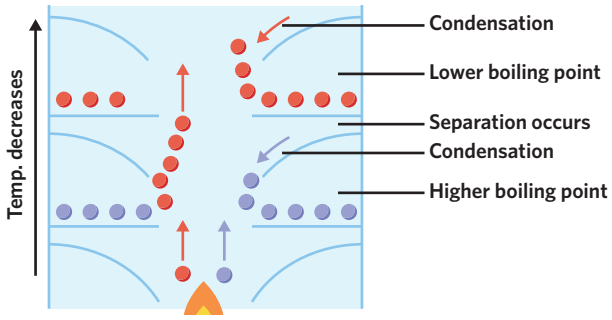


Figure 5 Fractional distillation column

If impurities are present, then the recorded boiling point will be higher (termed 'boiling point elevation') when compared to its known boiling temperature. One reason for this is that impurities can introduce additional intermolecular forces. For example, if an impurity has dipole-dipole interactions or hydrogen bonding, this may increase the overall strength of the intermolecular forces in the mixture; as a result, the boiling point may increase due to the stronger intermolecular forces holding the molecules together.

Additionally, impurities can disrupt the regularity and symmetry of the compound's crystal lattice or packing arrangement. This disruption can create defects or irregularities in the lattice structure, which in turn can increase the boiling point. The presence of impurities creates disruptions in the crystal lattice and thus increases the energy required to break the intermolecular forces and transition from a liquid to a vapour phase.

Furthermore, impurities can decrease the vapour pressure of the compound. Vapour pressure is the pressure exerted by the vapour in equilibrium with the liquid phase at a given temperature. When impurities are present, they reduce the number of available pure compound molecules at the surface and therefore decrease the vapour pressure. Consequently, a higher temperature is required to reach the necessary vapour pressure for boiling.

USEFUL TIP

Unlike melting points, the boiling point is affected by the external air pressure. The standard pressure at which boiling points are measured is 101.3 kPa.

Applications

Simple and fractional distillation techniques (figure 6) are extensively used in verifying both the purity and composition of liquid consumer products. They are commonly used in verifying the components of alcoholic beverages, essential oils, fragrances, and other chemical solvents. Measuring the boiling points is the preferred method for many volatile compounds, as the melting points of these compounds are often very low.

Techniques

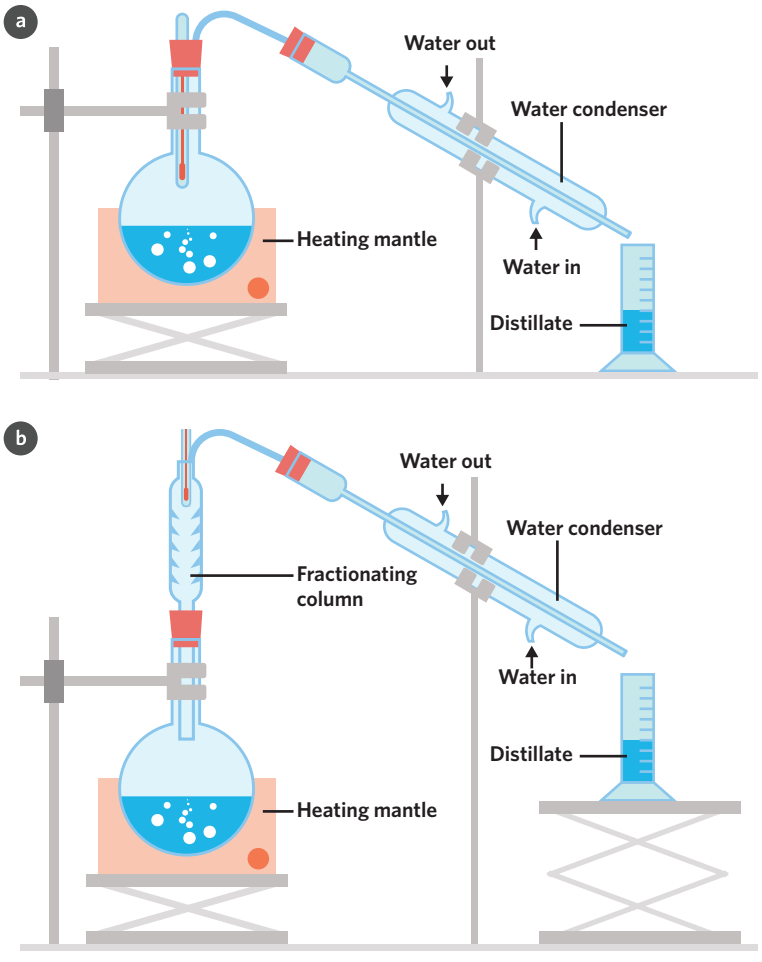


Figure 6 **(a)** Simple and **(b)** fractional distillation techniques

The main difference between the two techniques is the fractionating column, which allows continuous changes from liquid to gas and back to liquid again. This results in a much purer fraction than when using simple distillation, where mixtures need to be simply distilled multiple times in order to obtain a pure **distillate**. The boiling points of separated liquid fractions can verify components of the mixture as well as comparing them against the known temperature of the pure sample; if the temperature of the fraction is higher, then the component is not pure.

USEFUL TIP

Simple distillation is also commonly used to separate the solute (a solid) from the solvent (a liquid), which is not possible using fractional distillation.

PROGRESS QUESTIONS

Question 4

Boiling is best described as a

A. chemical change.
B. physical change.
C. chemical reaction.
D. breaking of covalent bonds.

Question 5

Boiling point determination using fractional distillation can be used to

A. identify the reactivity of the sample.
B. identify functional groups.
C. calculate the density of the sample.
D. verify the components of a sample.

Question 6

What effect do impurities have on the boiling point of a compound?

A. Increase
B. Decrease
C. Increase or decrease
D. No change

Theory summary

- Matter can be classified as either elements or compounds. Laboratory analysis techniques play a crucial role in verifying the purity of elements and compounds in consumer products.
- The melting point of a substance is the temperature at which the forces of attraction between molecules or ions are overcome and a change in physical state occurs from solid to liquid.
- Pure solid compounds melt at a sharp, well-defined temperature (very small temperature range of 1–2 °C) whereas impure, contaminated compounds exhibit a lower and broader melting range.
- The presence of impurities in a solid compound lowers its melting point by reducing the strength of intermolecular forces or destabilising the crystal lattice.
- Boiling point is the temperature at which the forces of attraction between atoms or ions are overcome and a change in physical state from liquid to gas occurs.
- Pure liquid compounds boil at a sharp, highly-defined temperature (very small temperature range of 1–2 °C) whereas impure, contaminated liquids exhibit a higher boiling point.
- The presence of impurities in a liquid will increase the boiling point of a compound by introducing additional intermolecular forces or disrupting the crystal lattice, and lowering the vapour pressure.
- A pure substance's melting point and boiling point are both sharp and well-defined.
- The stronger and more numerous the forces between the atoms or ions in a compound are, the higher the melting and boiling point will be.

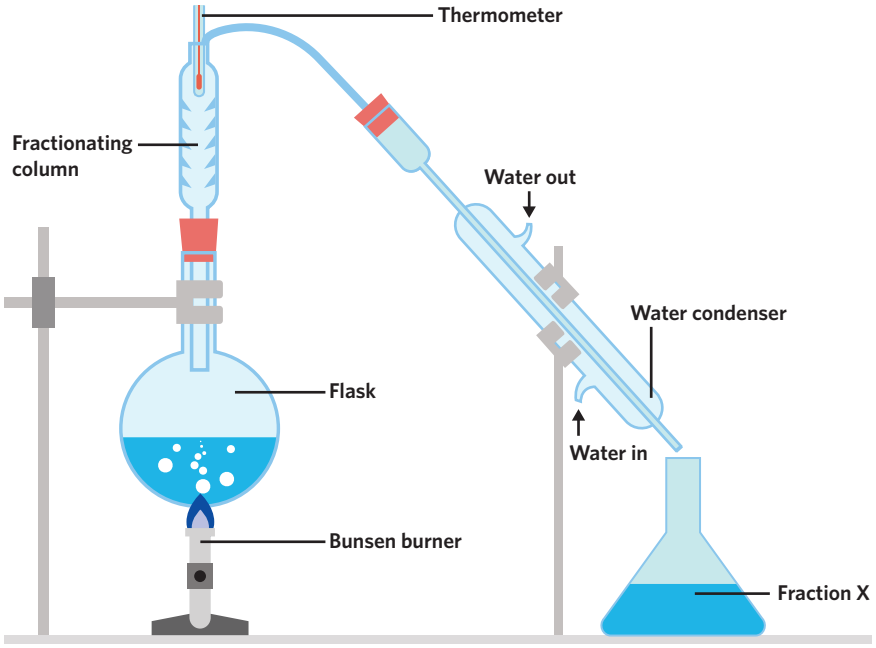
9B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

In a laboratory experiment, a skin oil (a mixture of pure substances) was analysed by separating it into its components using the following apparatus.



Question 7 (1 MARK)

The method shown is an example of

A. simple distillation.

B. fractional distillation.

C. melting point determination.

D. separating a solute from a solvent.

Question 8 (1 MARK)

Starting in the flask, which row correctly shows the changes in state that occur in the formation of the distillate?

A. Liquid → gas

B. Liquid → gas → liquid → gas

C. Liquid → gas ⇋ liquid

D. Liquid → gas ⇋ liquid→ gas → liquid

Question 9 (1 MARK)

The first fraction collected from the skin oil is fraction X, then fraction Y, then fraction Z.
From this information we can deduce that

A. fraction Y is more volatile than X.

B. fraction Z has a higher molar mass than X and Y.

C. fraction X has a higher boiling point than Y and Z.

D. fraction Z has stronger forces of attraction between its molecules than X and Y.

Adapted from VCAA 2008 Exam 1 Multiple choice Q20

Exam-style

Question 10 (1 MARK)

When determining the melting point of a pure medicinal compound with the solid and liquid phase in equilibrium, the temperature

A. increases.

B. decreases.

C. remains constant.

D. increases then decreases.

Question 11 (1 MARK)

Which of the following statements is incorrect?

A. All solid ionic and covalent compounds have a sharply defined melting point.

B. Impure solid substances or mixtures have lower melting points than when pure.

C. Melting point can be used as evidence of the purity of a solid substance.

D. Two pure substances cannot have very similar melting points.

Question 12 (1 MARK)

It was decided that a mixture of two different pure liquids of omega-3 fish oil, that have accurately known boiling points, should be separated by the method of fractional distillation. Which combination of boiling points for the two liquids best justifies the use of this method?

A. 534 K and 567 K

B. 534 K and 536 K

C. 473 K and 573 K

D. 473 K and 523 K

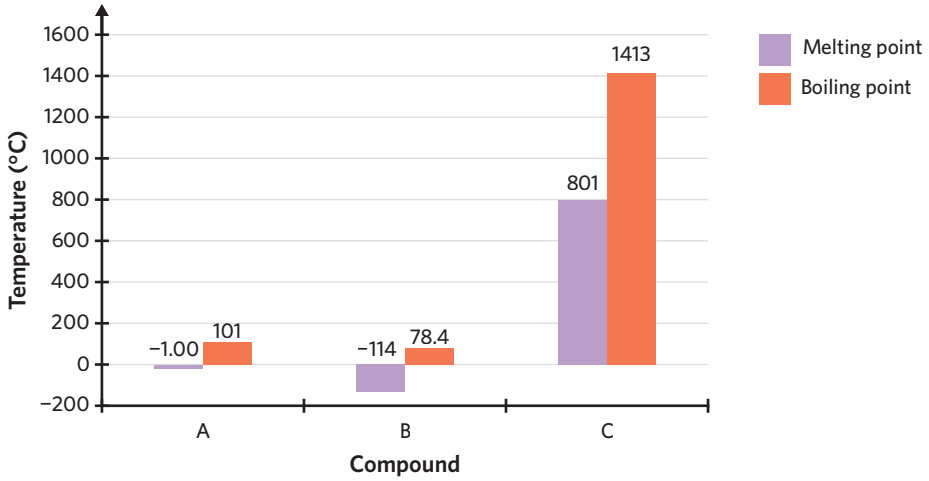
Question 13 (4 MARKS)

A pharmaceutical company is worried that their product (a solid tablet with one ingredient) is contaminated. Explain how the company could test the purity of the product, and (if necessary) separate their product from the contaminant.

Key science skills

Question 14 (11 MARKS)

A graph shows some of the physical properties of three compounds A, B, and C that are all components of a widely available skin cleanser.



a. Justify the most appropriate physical property and method that should be utilised in the separation of a mixture of compounds A, B, and C. 3 MARKS

b. How can compound C be separated from compounds A and B without having to use temperatures above 110 °C? 2 MARKS

c. Identify and explain the physical states of each of the compounds A, B, and C if the temperature of the mixture is 85 °C. 3 MARKS

d. Suggest a possible identity of compound A, and explain how this value of the melting point could occur. 3 MARKS

FROM LESSON 12C

Questions from multiple lessons

Question 15 🌶🌶🌶 (12 MARKS)

A fuel mixture contains several different organic liquids all of which boil at temperatures greater than 50 °C.

The compounds present in the mixture are separated. Three of the compounds, compounds Q, T, and M, are analysed as follows.

a. Compound Q is vaporised. At a temperature of 25.0 °C and a pressure of 100 kPa, a 0.371 g sample of the vapour occupies 124 mL. Calculate the molar mass, in g mol^{-1}, of compound Q. 2 MARKS

b. Compounds T and M are alcohols with the molecular formula $C_4H_{10}O$.

i. Draw the structural formulas, showing all bonds, and give the IUPAC names of the four possible alcohols with a molecular formula of $C_4H_{10}O$. 8 MARKS

ii. Alcohol T is able to be oxidised to a carboxylic acid, whereas alcohol M resists oxidation. Identify alcohols T and M. 2 MARKS

Adapted from VCAA 2008 Exam 1 Q4a, b

FROM LESSONS 2A, 7B & 8A

Back to contents

9C Volumetric analysis of redox reactions


Image: Cavan-Images/Shutterstock.com

Why are indicators not always added in redox titrations?

Redox **titrations** are a versatile **volumetric analysis** technique that can be used in a range of industries for quality control (vitamin C content), process optimisation (amount of sulfate in wine), and food monitoring (shelf-life of fats and oils). In this lesson, we will learn how to carry out redox titrations and use their results to determine an unknown value.

KEY TERMS AND DEFINITIONS

Aliquot portion of a sample solution used for analysis during titration
Concentration amount of chemical substance per unit of volume
Concordant titres three or more titres that fall within 0.1 mL of each other
End point point at which a colour change occurs during titration
Equivalence point point at which the reaction has occurred as per the stoichiometric ratio of the balanced equation
Indicator substance that changes colour to indicate the end point
Iodine value (IV) mass of iodine in grams that is consumed by 100 g of a fat or oil
Meniscus curved upper surface of liquid
Standardised solution solution of known concentration
Titration quantitative technique used to find the concentration and/or amount of substance in a solution
Titre volume of the solution delivered from the burette to reach the end point of a titration
Volumetric analysis quantitative analytical technique used to determine unknown concentrations of solutions

STUDY DESIGN DOT POINTS

- volumetric analysis, including calculations of excess and limiting reactants using redox titrations (excluding back titrations)
- measurement of the degree of unsaturation of compounds using iodine

9A 9B 9C

- 4.2.3.1 Principles of titration
- 4.2.3.2 & 4.2.3.3 Redox titrations & calculations involving redox titrations
- 4.2.4.1 Measuring the degree of unsaturation

ESSENTIAL PRIOR KNOWLEDGE

- The mole
- Indicators

7A Unsaturated

See questions 75–77.

Principles of titration 4.2.3.1

In this lesson, we will extend on the basics of acid-base titrations that were covered in VCE chemistry Unit 2.

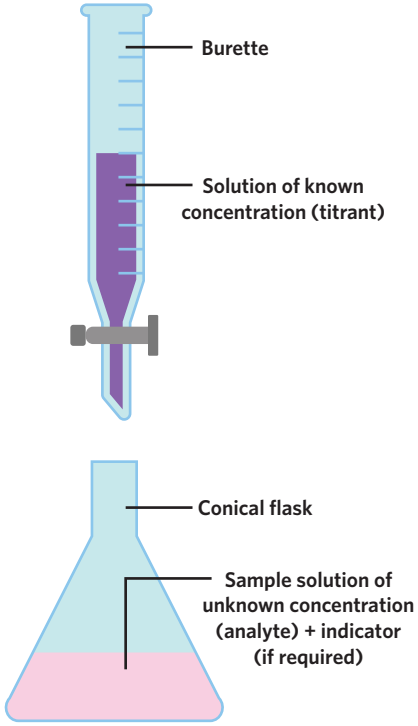


Figure 1 The basic setup for a titration reaction

MISCONCEPTION

'The solution of unknown concentration is always in the conical flask, and the solution of known concentration is always in the burette.'

Regardless of whether the unknown solution is in the conical flask or the burette, the principles of titration still apply.

Why do we use redox titrations?

Sometimes chemists deal with solutions of unknown **concentrations**. This may be because they are testing a random sample of water from a stream, or they want to see if they have prepared a solution correctly. The basic principle of titration is that by reacting a solution of known concentration with a solution of unknown concentration, chemists can use their understanding of volume-volume stoichiometry to calculate the concentration of the unknown solution.

As part of this process, a solution of known concentration is used to measure the amount or concentration of a substance in a sample solution of unknown concentration. A basic titration setup is shown in figure 1.

How do we carry out a titration?

To prepare a titration experiment, a pipette is used to transfer a known volume, called an **aliquot**, of a sample solution of unknown concentration (analyte) into the conical flask, along with the relevant **indicator**. The conical flask is placed under the burette, and the burette is usually then filled with a solution of known concentration. This solution is dispensed incrementally from the burette into the conical flask, resulting in a chemical reaction in the conical flask. The titrant is added until a permanent colour change is observed in the conical flask; this is called the **end point** of the titration. The titration process is summarised in figure 2.

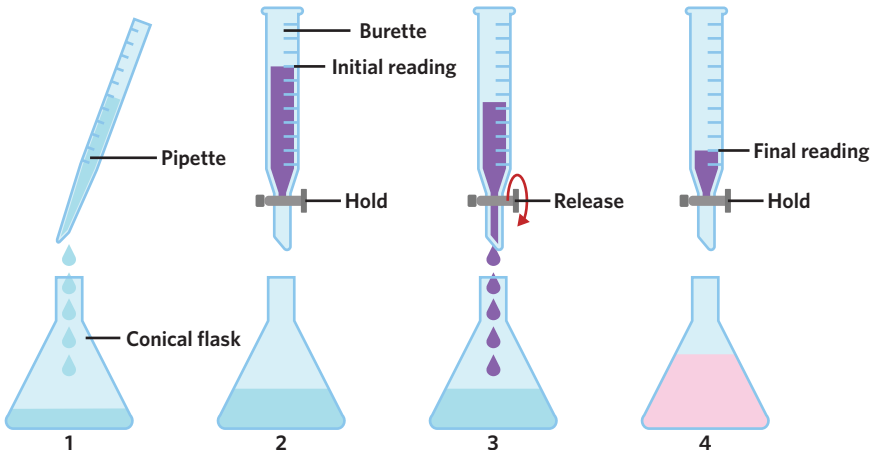


Figure 2 A summary of the titration process

MISCONCEPTION

'All titrations require the addition of an indicator.'

Some redox reactions are self-indicating and change colour without the addition of an indicator.

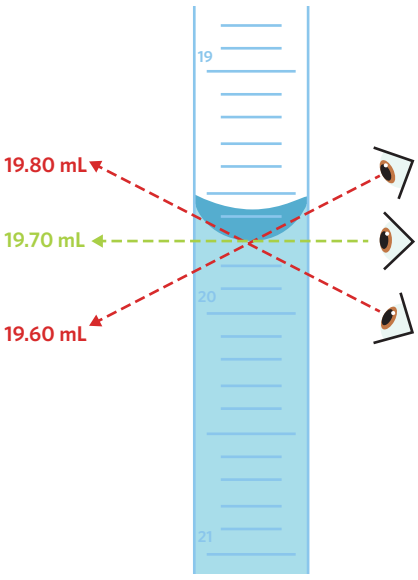


Figure 3 Reading a burette

It is important to note how to read these values from a burette correctly. Due to the way liquids interact with the walls of the burette, we will usually see a dip in the solution in the burette. Therefore, when we read the scale on a burette, we need to position ourselves so that our line of sight is horizontal to the bottom dip of the **meniscus**. If we don't align ourselves appropriately, the volume read will be higher or lower than the true value as illustrated in figure 3 (depending on whether we are lower or higher than the meniscus), making our results inaccurate. This is known as parallax error.

The experiment is repeated multiple times until **concordant titres** (usually all **titres** within $\pm$ 0.1 mL) are obtained to increase the reliability and precision of the results by minimising the effects of random errors. Table 1 shows an example of the type of data that is recorded during a titration experiment.

Table 1 Sample values from a titration

Titration number	1	2	3	4
Initial burette reading (mL)	3.50	7.30	13.35	0.00
Final burette reading (mL)	22.90	26.30	32.40	19.10
Titre volume (mL) (Final burette reading − initial burette reading)	19.40	19.00	19.05	19.10

In this case, titrations 2, 3 and 4 are concordant titres as they are titres that fall within a range of 0.1 mL from the highest value (19.10 mL) to the lowest value (19.00 mL). The average titre, which is used in calculations, is the average of the concordant titres. Therefore, in this example:

Average titre: $\frac{19.00\text{ mL} + 19.05\text{ mL} + 19.10\text{ mL}}{3} = 19.05\text{ mL}$

Note that typically the initial reading from the burette is lower than the final reading. This is because some burettes measure the total volume that has been dispensed, meaning '0.00 mL' is located at the very top of the burette.

MISCONCEPTION

'A titre of 19.02 mL can be read from a standard burette.'

The resolution of a standard burette is ± 0.05 mL, so the reading recorded would be 19.00 mL (19.02 mL is closer to 19.00 mL than 19.05 mL). Note that multiple readings from a burette could have an average of 19.02 mL, but not a single reading.

What are some common experimental errors during titrations?

Due to the practical nature of titration, experimental errors can be introduced in a variety of ways. Some common errors and their effects are described in table 2.

Table 2 Common errors during titrations and their effects

Situation	Effect on accuracy of calculated concentration, if unknown solution is in:		Explanation
	Conical flask	Burette	
Burette rinsed with water	Overestimated	Underestimated	Solution in burette becomes diluted
Pipette rinsed with water	Underestimated	Overestimated	Solution in conical flask becomes diluted
Conical flask rinsed with solution to fill it	Overestimated	Underestimated	Solution in conical flask has higher concentration of solute
Missed indicator end point	Overestimated	Underestimated	Bigger discrepancy between end point and **equivalence point**

PROGRESS QUESTIONS

Question 1

During a titration, a _____ is used to deliver a solution into a _____.

A. burette, measuring cylinder

B. burette, conical flask

C. conical flask, burette

D. conical flask, measuring cylinder

Question 2

What is the unit of c in the equation $n = c \times V$?

A. g mL^{-1}

B. g mol^{-1}

C. L mol^{-1}

D. mol L^{-1}

Continues →

Question 3

Which of the following can be used to calculate V?

A. $V = \frac{n}{c}$ **B.** $V = \frac{c}{n}$ **C.** $V = c \times n$ **D.** $V = n \times c$

Question 4

Which of the following options contains three concordant titres?

A. 17.65 mL, 18.50 mL, 19.50 mL, 19.00 mL, 17.00 mL

B. 17.65 mL, 17.50 mL, 18.05 mL, 18.00 mL, 17.85 mL

C. 17.65 mL, 17.80 mL, 18.05 mL, 17.65 mL, 17.60 mL

D. 17.65 mL, 17.50 mL, 18.05 mL, 18.00 mL, 17.65 mL

Redox titrations & calculations involving redox titrations 4.2.3.2 & 4.2.3.3

Redox titrations are used to determine the concentration of chemicals that can undergo a redox reaction. The main differences between acid-base and redox titrations are the indicators used and the details of the titration curves.

How do we determine when a redox reaction is complete?

As we learned in lesson 3A, reactions between certain chemicals can result in a redox reaction. Redox titrations are used to determine the concentration of an unknown solution of an oxidising or reducing agent. This can be done by reacting with a sample of a **standardised solution** of known concentration which is normally made up in a 250.0 mL volumetric flask. These standard solutions are often diluted which means that when the concentration of the original sample is required it must be scaled up according to the dilution factor.

When preparing a redox titration, if required, we need to add an appropriate indicator to the solution in the conical flask prior to dispensing the burette solution into the flask. After the addition of a specific volume of the burette solution, the solution in the conical flask will change colour. This colour change can be from one of the chemicals involved in the redox reaction or from the indicator.

The colour change that occurs represents the end point of the titration. This indicates that the reactants and products have reached a balanced stoichiometric ratio according to the balanced chemical equation for the equation; this is referred to as the equivalence point.

MISCONCEPTION

'The equivalence point and the end point are the same.'

The equivalence point represents the end of the chemical reaction. The end point, however, describes the colour change that follows the equivalence point.

What are some examples of redox titrations?

Table 3 gives examples of different redox titrations that can be investigated. Potassium permanganate is the preferred choice of oxidising agent as potassium dichromate is too dangerous to use in schools.

MISCONCEPTION

'All oxidising and reducing agents change pH when they react together.'

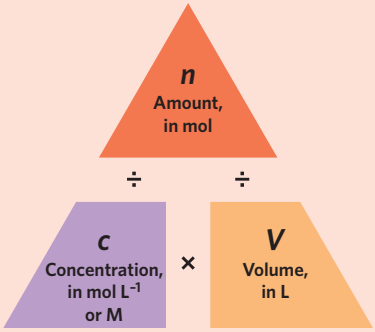
Most of these types of reactions do not have a change in pH; instead, they are measured using their electrode potentials (E^0) measured in volts (V).

Table 3 Examples of reducing and oxidising agents that can be used in redox titrations

Oxidising agent (solution)	Reducing agent (solution)	Conditions	Indicator and colour change	Equation
Potassium(VI) dichromate	Iron(II)	Acid	Diphenylamine green ⇌ violet	$Cr_2O_7^{2-}(aq) + 6Fe^{2+}(aq) + 14H^+(aq) \rightarrow 2Cr^{3+}(aq) + 6Fe^{3+}(aq) + 7H_2O(l)$
Potassium(VI) dichromate	Potassium iodide	Acid	Diphenylamine green ⇌ violet	$K_2Cr_2O_7(aq) + 7H_2SO_4(aq) + 6KI(aq) \rightarrow Cr_2(SO_4)_3(aq) + 7H_2O(l) + 3I_2(aq) + 4K_2SO_4(aq)$ or $Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6I^-(aq) \rightarrow 2Cr^{3+}(aq) + 3I_2(aq) + 7H_2O(l)$
Potassium(VII) permanganate	Iron(II)	Acid	Self-indicating purple ⇌ pale pink	$MnO_4^-(aq) + 5Fe^{2+}(aq) + 8H^+(aq) \rightarrow 5Fe^{3+}(aq) + Mn^{2+}(aq) + 4H_2O(l)$
Potassium(VII) permanganate	Ethanedioic acid (oxalic acid)	Acid	Self-indicating purple ⇌ pale pink	$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \rightarrow 2Mn^{2+}(aq) + 10CO_2(g) + 8H_2O(l)$
Potassium(VII) permanganate	Hydrogen peroxide	Acid	Self-indicating purple ⇌ pale pink	$2MnO_4^-(aq) + 5H_2O_2(aq) + 6H^+(aq) \rightarrow 5O_2(g) + 2Mn^{2+}(aq) + 8H_2O(l)$
Potassium(VII) permanganate	Hydrogen peroxide	Alkali	Self-indicating purple ⇌ brown	$2MnO_4^-(aq) + 3H_2O_2(aq) \rightarrow 2MnO_2(s) + 3O_2(g) + 2H_2O(l) + 2OH^-(aq)$
Iodine produced from a mix of KI/KIO_3	Sodium thiosulfate	Acid	Starch colourless ⇌ yellow ⇌ dark blue	$I_2(aq) + 2S_2O_3^{2-}(aq) \rightarrow 2I^-(aq) + S_4O_6^{2-}(aq)$
Copper(II) then iodine	Iodide ions then sodium thiosulfate	KI solution	Starch colourless ⇌ yellow ⇌ dark blue	Reaction 1: $2I^-(aq) + Cu^{2+}(aq) \rightarrow I_2(aq) + Cu(s)$ Reaction 2: $I_2(aq) + 2S_2O_3^{2-}(aq) \rightarrow 2I^-(aq) + S_4O_6^{2-}(aq)$
Sulfur dioxide (in wine)	Iodine	Acid	Starch colourless ⇌ yellow ⇌ dark blue	$SO_2(aq) + I_2(aq) + 2H_2O(l) \rightarrow 4H^+(aq) + SO_4^{2-}(aq) + 2I^-(aq)$
Citric acid	Iodine	Acid	Starch colourless ⇌ yellow ⇌ dark blue	$C_6H_8O_6(aq) + I_2(aq) \rightarrow C_6H_6O_6(aq) + 2H^+(aq) + 2I^-(aq)$

STRATEGY

We can use the following concept triangle to help us figure out the type of calculation to perform to find the concentration, amount of solute or even volume of solutions.



To use this, use your finger to cover up the value you are trying to find. Calculate using the remaining variables as indicated by the signs. For example, to find the amount, cover the section of the triangle that says 'amount', which leaves us to perform the calculation $c \times V$.

USEFUL TIP

Concentrations and volumes can be expressed using different units. Therefore, it is important to ensure that the values are in the same appropriate units (mol L^{-1}, or its shorthand 'M', for concentration) before the equation can be used to determine the number of moles of a substance present.

How do we calculate an unknown concentration in redox titrations?

The values obtained from a titration reaction can be used to determine unknown concentrations of any of the substances involved in the redox reaction.

WORKED EXAMPLE 1

How many moles of $Cr^{6+}(aq)$ are present in 200 mL of 0.25 mol L^{-1} $Cr_2O_7^{2-}(aq)$ solution?

What information is presented in the question?

Volume of solution, V: 200 mL.

Concentration of solution, c: 0.25 mol L^{-1}.

What is the question asking us to do?

Find the number of moles of $Cr^{6+}(aq)$ dissolved in the solution.

What strategies do we need in order to answer the question?

1. Substitute the volume and concentration of $Cr_2O_7^{2-}(aq)$, using the appropriate units, into the equation $n = c \times V$.
2. Dissolved $Cr_2O_7^{2-}$ can be expressed as $2Cr^{6+}(aq) + 7O^{2-}(aq)$.

Answer

$n = c \times V$

$c(Cr_2O_7^{2-}) = 0.25 \text{ mol L}^{-1}$

$V(Cr_2O_7^{2-}) = \left(\frac{200 \text{ mL}}{1000}\right)$

$V(Cr_2O_7^{2-}) = 0.200 \text{ L}$

$n(Cr_2O_7^{2-}) = 0.25 \text{ mol L}^{-1} \times 0.200 \text{ L}$

$n(Cr_2O_7^{2-}) = 0.050 \text{ mol}$

$n(Cr_2O_7^{2-}) : n(Cr^{6+})$

$1 \quad : \quad 2$

$n(Cr^{6+}) = \frac{2}{1} \times n(Cr_2O_7^{2-})$

$n(Cr^{6+}) = 2 \times 0.050 \text{ mol}$

$n(Cr^{6+}) = 0.10 \text{ mol (2 sig. figs)}$

USEFUL TIP

If volume is given in mL, convert this value to L by dividing by 1000 before using the formula $n = c \times V$.

WORKED EXAMPLE 2

What is the volume, in mL, of a 0.750 mol L^{-1} solution containing 0.500 mol of $H_2O_2(aq)$?

What information is presented in the question?

Concentration of solution, c: 0.750 mol L^{-1}.

Number of moles in solution, n: 0.500 mol.

What is the question asking us to do?

Calculate the volume of the solution.

What strategies do we need in order to answer the question?

1. Rearrange the equation $n = c \times V$ to make V the subject.
2. Substitute the concentration and number of moles of $H_2O_2(aq)$ into the rearranged equation using the appropriate units.
3. Convert volume into mL.

Answer

$n = c \times V$

Rearranged: $V = \frac{n}{c}$

$V = \frac{0.500 \text{ mol}}{0.750 \text{ mol L}^{-1}}$

$V = 0.6666 \text{ L}$

Conversion from L to mL:

$0.6666 \text{ L} \times 1000 = 666.6 \text{ mL}$

$V = 667 \text{ mL (3 sig. figs)}$

WORKED EXAMPLE 3

In a self-indicating redox titration, an average concordant titre of 24.10 mL of a 0.50 mol L^{-1} standardised solution of iron(II) sulfate, $FeSO_4(aq)$, was used to react with a 25.00 mL aliquot, which was taken from a 250.0 mL sample of acidified potassium permanganate solution, $KMnO_4(aq)$. The balanced equation for the reaction is given.

$MnO_4^-(aq) + 8H^+(aq) + 5Fe^{2+}(aq) \rightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Fe^{3+}(aq)$

Determine the concentration (in mol L^{-1}) of the potassium permanganate solution.

What information is presented in the question?

Average titre (24.10 mL).

Concentration (0.50 mol L^{-1}) of iron(II) sulfate.

Volume of potassium permanganate (25.00 mL) taken from a 250.0 mL volumetric flask.

The balanced equation for the redox reaction between iron(II) sulfate and potassium permanganate.

What is the question asking us to do?

Determine the concentration of the potassium permanganate solution.

What strategies do we need in order to answer the question?

1. Determine the amount of iron(II) sulfate used in the reaction using $n = c \times V$.
2. Use stoichiometry to determine the mole ratio of $n(FeSO_4) : n(KMnO_4)$.
3. Determine the amount of potassium permanganate present in the 250.0 mL volumetric flask.
4. Determine the concentration (in mol L^{-1}) of the potassium permanganate solution.

Answer

$n(FeSO_4) = c \times V$

$n(FeSO_4) = 0.50 \text{ mol L}^{-1} \times \left(\frac{24.10}{1000}\right) \text{L}$

$n(FeSO_4) = 0.01205 \text{ mol}$

According to the balanced equation for the reaction,

$n(FeSO_4) : n(KMnO_4)$

5 : 1

$n(KMnO_4) = \frac{0.01205 \text{ mol}}{5}$

$n(KMnO_4) = 0.002410 \text{ mol}$ (in 25.00 mL aliquot)

$c(KMnO_4) = \frac{n}{V}$

In the volumetric flask (250.0 mL sample)

$n(KMnO_4) = 0.002410 \text{ mol} \times \frac{250.0 \text{ mL}}{25.00 \text{ mL}}$

$n(KMnO_4) = 0.02410 \text{ mol in } 250.0 \text{ mL}$

Scale up to 1.00 L

$c = \frac{n}{V}$

$c(KMnO_4) = 0.02410 \text{ mol} \times \frac{1000 \text{ mL}}{250.0 \text{ mL}}$

or $c(KMnO_4) = \frac{0.02410 \text{ mol}}{0.2500 \text{ L}}$

or combining two steps by scaling directly from 25.00 mL to 1000 mL

$n(KMnO_4) = 0.02410 \text{ mol in } 25.00 \text{ mL} \times \frac{1000 \text{ mL}}{25.00 \text{ mL}}$

$c(KMnO_4) = 9.6 \times 10^{-2} \text{ mol L}^{-1}$ (2 sig. figs)

An overall summary of the calculations used following a titration is shown in figure 4.[1]

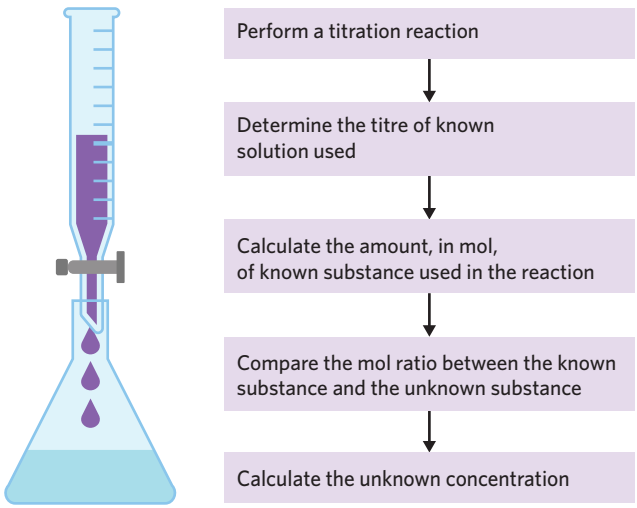


Figure 4 Calculating the concentration of an unknown solution using titration

KEEN TO INVESTIGATE?

[1] **How can the amount of ethanol in wine be determined?**
Search YouTube: Back Titration Alcohol Content

How do we calculate limiting and excess concentrations in redox reactions?

In lesson 1D, the availability of gaseous reactants in combustion reactions was discussed in terms of how it affects the amounts of products formed. Limiting reagents and reactants involving solutions are another type of reaction that is influenced by the amount of reactants available.

How can we determine limiting and excess reagents?

To determine the products formed in a chemical reaction and their quantities, we often have to consider limiting and excess reagents.

WORKED EXAMPLE 4

20.0 mL of 0.010 M iodine solution reacts with 20 mL of 0.0050 M sodium thiosulfate solution according to the following reaction.

$I_2(aq) + 2Na_2S_2O_3(aq) \rightarrow 2NaI(aq) + Na_2S_4O_6(aq)$

Identify the limiting reactant in the reaction outlined above.

What information is presented in the question?

The concentration and volume of each reactant.

The balanced chemical equation showing the reaction between iodine and sodium thiosulfate.

What is the question asking us to do?

Determine which reactant is limiting.

What strategies do we need in order to answer the question?

1. Determine the amount of $I_2(aq)$ and $2Na_2S_2O_3(aq)$ available in the reaction using $n = c \times V$.
2. Use stoichiometry from the balanced equation to determine the mole ratio of $I_2(aq) : Na_2S_2O_3(aq)$.
3. Determine which reagent is limiting.

Answer

$n(I_2) = c \times V$

$n(I_2) = 0.010 \text{ mol L}^{-1} \times \left(\frac{20.0}{1000}\right) \text{L}$

$n(I_2) = 0.00020 \text{ mol or } 2.0 \times 10^{-4} \text{ mol}$

$n(Na_2S_2O_3) = c \times V$

$n(Na_2S_2O_3) = 0.0050 \text{ mol L}^{-1} \times \left(\frac{20.0}{1000}\right) \text{L}$

$n(Na_2S_2O_3) = 0.00010 \text{ mol or } 1.0 \times 10^{-4} \text{ mol}$

Given that $Na_2S_2O_3(aq)$ reacts with I_2 in a ratio of 2 : 1, 4.00×10^{-4} mol of $Na_2S_2O_3(aq)$ would be required to react completely with 2.0×10^{-4} mol of $I_2(aq)$.

Therefore, the limiting reagent is $Na_2S_2O_3(aq)$ as only 5.0×10^{-5} mol of $I_2(aq)$ will react, whereas all of the $Na_2S_2O_3(aq)$ will react.

PROGRESS QUESTIONS

Question 5

When the indicator changes colour, this signals that the _____ has been reached.

A. equivalence point

B. indicator point

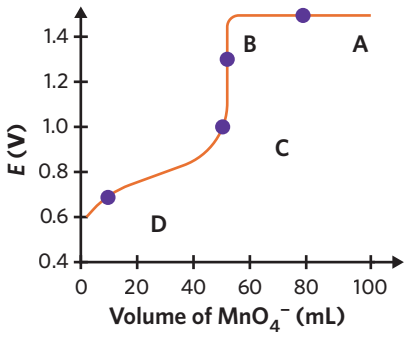
C. end point

D. pH point

Continues →

Question 6

As redox reactions do not typically involve a change in pH, the equivalence point is instead found by plotting the electrode potential, *E*, against the volume, mL. Which point on the graph represents the equivalence point?



A. A **B.** B **C.** C **D.** D

Question 7

Which of the following is not a commonly used oxidising agent as it is too hazardous for use in schools?

A. Potassium(VI) dichromate

B. Potassium(VII) permanganate

C. Hydrogen peroxide

D. Sodium thiosulfate

Measuring the degree of unsaturation 4.2.4.1

Lipids can be categorised into two main groups, fats and oils. They are categorised according to their state at room temperature with fats being solid and oils being liquid. Fats and oils contain different degrees of unsaturation (number of carbon-carbon double bonds). Fats have a much lower degree of unsaturation, whereas oils have a much higher degree of unsaturation (table 4).

Table 4 Approximate proportions and states of some common fats and oils

Lipid	Approximate proportions		State at room temperature (°C)	Classification
	Saturated (%)	Unsaturated (%)		
Coconut	89	11	Solid	Fat
Butter	70	30	Solid	Fat
Olive oil	25	75	Liquid	Oil
Sunflower oil	12	88	Liquid	Oil
Canola oil	6	94	Liquid	Oil

USEFUL TIP

The more unsaturated a fat or oil is, the more reactive it is in the body. This means it can be readily used by the body instead of being stored.

How can the degree of unsaturation of a fat or oil be quantified using redox reactions?

The degree of unsaturation can be quantified relative to its **iodine value (IV)** or iodine number. The iodine value is a measure of the unsaturation in a fat or oil. It is defined as the number of grams of iodine that react with 100 grams of fat or oil. The higher the iodine value, the more unsaturated the fat or oil is. An example of how an iodine value can be determined for an oil is shown.

USEFUL TIP

The more carbon-carbon double bonds molecules have, the more loosely they are attracted to each other, which results in a liquid (oil). Conversely, having fewer double bonds allows molecules to pack and bond more tightly together, resulting in a solid (fat).

The carbon-carbon double bonds in a fat or oil react with Wijs solution (iodine monochloride in glacial ethanoic acid) resulting in the addition of iodine and chlorine across the double bond. Figure 5 shows how this reaction occurs with linolenic acid that has been dissolved in an organic solvent.

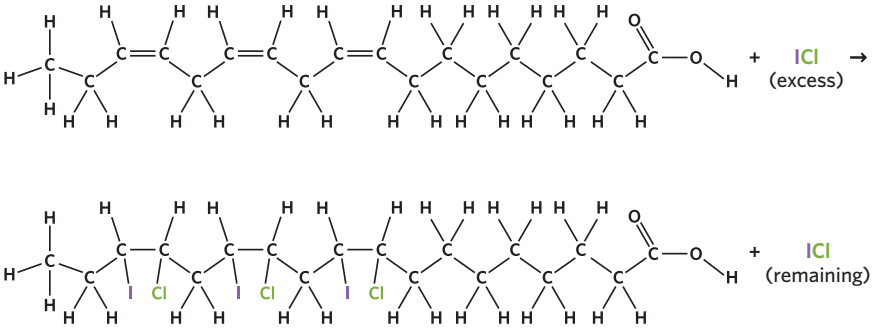


Figure 5 Linolenic acid has three double bonds and reacts with excess ICl.

After leaving the reaction in a dark room, the amount of iodine that has reacted is determined by adding an excess solution of potassium iodide and distilled water to the reaction product.

$$ICl(aq) + KI(aq) \rightarrow KCl(aq) + I_2(aq)$$

This causes the remaining unreacted ICl to form molecular iodine. The liberated I_2 is then titrated using a redox reaction with 0.10 M sodium thiosulphate solution using freshly prepared starch solution as indicator, which is added towards the end of the titration, causing a change from dark blue to colourless.

$$I_2(aq) + 2Na_2S_2O_3(aq) \rightarrow 2NaI(aq) + Na_2S_4O_6(aq)$$

This will give a volume (V_{sample}) for the oil sample. The procedure is then repeated without any sample of the oil and the volume (V_{blank}) required to change the starch from dark blue to colourless is recorded.[2]

KEEN TO INVESTIGATE?

[2] **How exactly do you experimentally determine an iodine value?**
Search YouTube: Determination of Iodine Value - A Complete Procedure

An example of an iodine value (IV) calculation using the fat linolenic acid is shown:

Mass of oil	0.25 g
Titre with the oil sample (V_{sample})	59.55 mL
Blank titre (V_{blank})	65.05 mL
Concentration of sodium thiosulfate	0.10 M

The following formula is used to calculate an iodine value (IV).

$$IV = \frac{(V_{blank} - V_{sample}) \times 0.10\ M \times 126.9\ g\ mol^{-1}}{\text{mass of sample (g)}}$$

Note: the molecular mass of iodine is 126.9 g mol^{-1}

Substitute in the relevant data.

$$IV_{linolenic\ acid} = \frac{(65.05\ mL - 59.55\ \ mL) \times 0.10\ M \times 126.9\ g\ mol^{-1}}{0.25\ g}$$

$$IV_{linolenic\ acid} = 279$$

This indicates that this fat is polyunsaturated.

If the iodine number is between 0 and 70, it contains a small proportion of unsaturated fat, and if the value exceeds 70 it contains a large proportion of unsaturated oil (table 5). The iodine value is important in food chemistry because it provides information about the chemical structure and properties of fats and oils. Unsaturated fats and oils are more reactive and prone to oxidation, which can lead to the food becoming inedible. Therefore, the iodine value can be used to predict the shelf-life and stability of fats and oils.

Table 5 Typical iodine numbers for some common fats and oils

Lipid	Iodine value (IV)	State at room temperature (°C)	Classification
Coconut	6–11	Solid	Fat
Butter	25–40	Solid	Fat
Olive oil	75–95	Liquid	Oil
Sunflower oil	80–110	Liquid	Oil
Canola oil	125–135	Liquid	Oil

MISCONCEPTION

'Coconut oil is an oil at room temperature.'

Given that coconut is mainly saturated fat and is a solid at room temperature it should be called coconut fat.

PROGRESS QUESTIONS

Question 8

Iodine monochloride reacts with fats and oils due to the presence of

A. a carbon-carbon single bond.

B. a carbon-carbon double bond.

C. a carbonyl bond.

D. an ester bond.

Theory summary

- Titration is a quantitative analysis technique used to determine the unknown concentration of a solution and/or the amount of a compound in a solution.
- The equivalence point is the point at which the ratio of oxidising agent to reducing agent present is equivalent to their stoichiometric ratio.
- The end point is the point at which the indicator changes colour.
- Many redox titrations are self-indicating, such as those involving $KMnO_4(aq)$ and $I_2(aq)$.
- Redox titration calculations follow a general sequence:
  - Determine the amount, in mol, of the substance of known concentration used in the reaction using $n = c \times V$.
  - Use stoichiometry from the balanced equation to determine the mole ratio of the known to unknown.
  - Either multiply or divide by the ratio accordingly to determine the mol of unknown present in the sample.
  - Scale up the volume or convert the volume to a concentration M (mol L^{-1}) as required.
- Limiting reagents can affect the amount of products formed in a redox reaction.
- The higher the iodine value (IV), the more unsaturated the fat or oil is.
- The iodine value (IV) is mass of iodine in grams that is consumed by 100 grams of a fat or oil and can be calculated using

$$\text{IV} = \frac{\left(V_{\text{blank}} - V_{\text{sample}}\right) \times 0.10\ \text{M} \times 126.9\ \text{g mol}^{-1}}{\text{mass of sample (g)}}$$

9C Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 9–11.

The concentration of vitamin C in a filtered sample of grapefruit juice was determined by titrating the juice with 9.367×10^{-4} M iodine, $I_2(aq)$, using starch solution as an indicator. The molar mass of vitamin C is 176.0 g mol^{-1}. The reaction can be represented by the following equation.

$$C_6H_8O_6(aq) + I_2(aq) \rightarrow C_6H_6O_6(aq) + 2H^+(aq) + 2I^-(aq)$$

Question 9 (1 MARK)

What type of chemical reaction occurs between citric acid and iodine solutions?

A. Neutralisation
B. Combustion
C. Elimination
D. Redox

Question 10 (1 MARK)

If the measured titre of iodine was 21.50 mL, what was the amount of vitamin C in the grapefruit juice sample that reacted with the iodine?

A. 0.00002014
B. 0.0009372
C. 0.009372
D. 0.02014

Question 11 (1 MARK)

The following method was used:

1. Weigh a clean 250 mL conical flask.
2. Use a 10 mL measuring cylinder to measure 5 mL of grapefruit juice into the conical flask.
3. Add 20 mL of deionised water to the conical flask.
4. Add a drop of starch solution to the conical flask.
5. Titrate the diluted grapefruit juice against the I_2 solution.

Which one of the following errors would result in an underestimation of the concentration of vitamin C in grapefruit juice?

A. 19 mL of deionised water was added to the conical flask.
B. The concentration of the I_2 solution was actually 9.178×10^{-4} M.
C. The initial volume of the I_2 solution in the burette was 1.50 mL, but it was read as 2.50 mL.
D. The measuring cylinder was inaccurate and the measured volume of grapefruit juice was higher than the actual volume.

Adapted from VCAA 2019 exam Multiple choice Q29, 30

Exam-style

Use the following information to answer questions 12–15.

A clear, colourless liquid extract of the rhubarb plant was analysed for the concentration of oxalic acid, $H_2C_2O_4$, by direct titration with a recently standardised and acidified potassium permanganate solution, $KMnO_4(aq)$.

The balanced equation for this titration is shown.

$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \rightarrow 2Mn^{2+}(aq) + 10CO_2(aq) + 8H_2O(l)$

The steps in the titration were as follows:

Step 1 A 20.00 mL aliquot of the rhubarb extract was placed in a 200 mL conical flask.

Step 2 The burette was filled with acidified 0.0200 M $KMnO_4$ solution.

Step 3 The acidified 0.0200 M $KMnO_4$ solution was titrated into the rhubarb extract in the conical flask. The titration was considered to have reached the end point when the solution in the conical flask showed a permanent change in colour. The volume of the titre was recorded.

Step 4 The titration was repeated until three concordant results were obtained. The average of the concordant titres was 21.70 mL.

Question 12 (1 MARK)

What piece of glassware should be used to measure the 20.0 mL aliquot of rhubarb extract?

A. Measuring cylinder

B. Analytical balance

C. Beaker

D. Pipette

Question 13 (1 MARK)

What would the expected colour change be for the reaction that occurs in the conical flask?

A. Yellow to colourless

B. Purple to colourless

C. Colourless to yellow

D. Colourless to purple

Question 14 (1 MARK)

Which of the following rinses is least likely to affect the accuracy of the results?

	Item	Rinse solution
A.	Burette	Distilled water
B.	Burette	Rhubarb extract
C.	Pipette	$KMnO_4(aq)$
D.	Conical flask	Distilled water

Adapted from VCAA 2018 exam Multiple choice Q18

Question 15 (3 MARKS)

Calculate the concentration, in mol L^{-1}, of $H_2C_2O_4$ in the rhubarb extract.

Adapted from VCAA 2018 exam Multiple choice Q17

Question 16 (3 MARKS)

After reacting fully with iodine, 0.25 g of an unknown oil consumed 1.50 mL of 0.10 M sodium thiosulfate solution.

a. Calculate its iodine value (IV). 2 MARKS

b. Using table 4, comment on the degree of saturation and likely state at room temperature. 1 MARK

Question 17 (3 MARKS)

When performing a redox titration, the concentration of the oxidising agent solution in the conical flask was too large for the reducing agent solution, and therefore, was diluted. The solution was diluted by a factor of 10.

If this redox titration had a stoichiometric ratio of 1 : 1 of oxidising agent to reducing agent, and 16.00 mL of a 1.0 mol L^{-1} reducing agent solution was used to reach the end point against a 20.00 mL aliquot of the solution of oxidising agent, after the above dilution, what is the concentration of the oxidising agent in the undiluted solution?

Key science skills

Question 18 (14 MARKS)

It is important in titrations to wash the glassware before using it. This is because the glassware may not have been washed correctly or at all before being packed away. In one redox titration, a student added 25.00 ml of 1.00 mol L^{-1} potassium permanganate solution to a 20.0 mL aliquot of 1.00 mol L^{-1} ethanedioic acid.

$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + 16H^+(aq) \rightarrow 2Mn^{2+}(aq) + 10CO_2(aq) + 8H_2O(l)$

a. Which reagent is limiting and what additional volume (in mL) would be required for a complete reaction to occur? 6 MARKS

b. This titration is repeated using an ethanedioic acid solution with unknown concentration. If the burette is washed with water, what effect would this have on the accuracy of the calculated concentration of ethanedioic acid? Justify your answer. 3 MARKS

c. Why is the conical flask washed with distilled water rather than the ethanedioic acid? 2 MARKS

d. Glassware is fragile and can be easily broken. Unfortunately, a student accidentally knocks over a retort stand and the burette, along with the potassium permanganate inside, is knocked to the floor and smashes. Suggest three safety precautions that have to be taken to minimise the effect of this incident. 3 MARKS

FROM LESSONS 12B & 12D

Questions from multiple lessons

Question 19 (9 MARKS)

The amount of iron in a newly developed, heat-resistant aluminium alloy is to be determined. An 80.50 g sample of the alloy is dissolved in concentrated hydrochloric acid and the iron atoms are converted to $Fe^{2+}(aq)$ ions. This solution is accurately transferred to a 250.0 mL volumetric flask and made up to the mark. 20.00 mL aliquots of this solution are then titrated against a standard 0.0400 M potassium permanganate solution.

$MnO_4^-(aq) + 8H^+(aq) + 5Fe^{2+}(aq) \rightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Fe^{3+}(aq)$

Four titrations were carried out and the volumes of potassium permanganate solution used were recorded in the table below.

Titration number	1	2	3	4
Volume of $KMnO_4$ (mL)	22.05	20.25	21.95	22.00

a. Write a balanced half-equation, including states, for the conversion of MnO_4^- ions, in an acidic solution, to Mn^{2+} ions. 2 MARKS

b. Calculate the average volume, in mL, of the concordant titres of the potassium permanganate solution. 1 MARK

c. Use your answer to part **b** to calculate the amount, in mol, of $MnO_4^-(aq)$ ions used in this titration. 1 MARK

d. Calculate the amount, in mol, of $Fe^{2+}(aq)$ ions present in the 250.0 mL volumetric flask. 2 MARKS

e. Calculate the percentage, by mass, of iron in the 80.50 g sample of alloy. Express your answer to the correct number of significant figures. 3 MARKS

Adapted from VCAA 2010 Exam 1 Short answer Q1

FROM LESSON 3B

Chapter 9 review

Mild Medium Spicy

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Which of the following is **not** a method that can be used to identify a carboxylic acid?

A. Lucas test
B. Universal indicator
C. Acid-base indicator
D. Neutralisation reaction

Question 2 (1 MARK)

If an impurity contaminated a medicinal compound that is solid at room temperature, its melting point would

A. decrease.
B. increase.
C. not change.
D. increase and decrease.

Question 3 (1 MARK)

The boiling point of a mixture of compounds that are found in methylated spirits is dependent on

A. the strength of the intermolecular forces.
B. the composition of the liquid compound.
C. the size of the molecules.
D. All of the above.

Question 4 (1 MARK)

The melting points of one of the four compounds contained within a powdered laundry detergent was tested. Which of the melting points indicates that the compound tested is present in a high purity?

A. 91–99 **B.** 68.5 **C.** 25–40 **D.** 8–12

Question 5 (1 MARK)

The main difference between simple and fractional distillation is

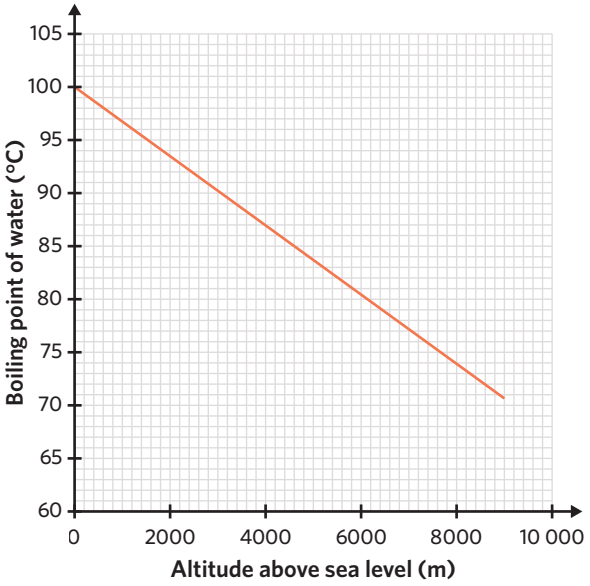
A. the number of components that can be separated.
B. the number of times the change liquid $\rightleftharpoons$ gas occurs.
C. the maximum temperature that can be reached.
D. the use of a condenser.

Question 6 (1 MARK)

Which of the following solutions **cannot** be used as a self-indicating oxidising agent in redox titrations?

A. Potassium(VI) dichromate
B. Potassium(VII) permanganate
C. Sodium thiosulfate
D. Iodine

Use the following information to answer questions 7–8.



Height (m)	Mountain
8848	Everest
2228	Kosciuszko

Question 7 🌶🌶 (1 MARK)

What is the best explanation for the trend shown in the graph?

A. At a higher altitude, atmospheric pressure is lower so it takes more energy to boil water.

B. At a higher altitude, atmospheric pressure is higher so it takes less energy to boil water.

C. At a higher altitude, atmospheric pressure is lower so it takes less energy to overcome the forces of attraction between liquid water molecules.

D. At a higher altitude, atmospheric pressure is lower so it takes more energy to overcome the forces of attraction between liquid water molecules.

Question 8 🌶🌶 (1 MARK)

Which of the following is **closest** to the percentage change in boiling points of pure water from the summit of Mount Everest to Mount Kosciuszko?

A. 20% **B.** 30% **C.** 40% **D.** 50%

Question 9 🌶🌶🌶 (1 MARK)

25.0 mL of 0.015 M iodine solution reacts with 20 mL of 0.00600 M sodium thiosulfate solution according to the following reaction.

$I_2(aq) + 2Na_2S_2O_3(aq) \rightarrow 2NaI(aq) + Na_2S_4O_6(aq)$

What is the number of moles of the excess reactant remaining in the reaction?

A. 1.2×10^{-4} mol $Na_2S_2O_3(aq)$

B. 3.15×10^{-4} mol $I_2(aq)$

C. 3.75×10^{-4} mol $I_2(aq)$

D. 0.00600 mol $Na_2S_2O_3(aq)$

Question 10 🌶🌶🌶 (1 MARK)

After reacting fully with iodine, 0.30 g of an unknown fat consumed 1.10 mL of 0.10 M sodium thiosulfate solution. What is the iodine value (IV) of the fat?

A. 11 **B.** 30 **C.** 47 **D.** 127

Short answer (30 MARKS)

Question 11 (7 MARKS)

Without sulfur dioxide, wines can undergo further fermentation reactions that cause unpleasant flavours.

The concentration of sulfur dioxide can be determined through a redox titration using iodine solution.

$SO_2(aq) + I_2(aq) + 2H_2O(l) \rightarrow 4H^+(aq) + SO_4^{2-}(aq) + 2I^-(aq)$

In order to prepare the wine sample for titration, 25.00 mL of wine was transferred to a volumetric flask and the flask was filled to the 100.0 mL mark with deionised water. An average titre of 14.95 mL of a 0.100 M iodine solution was used to react with a 20.00 mL aliquot of wine.

a. Which reactant is acting as the oxidising agent? 1 MARK

b. Suggest a suitable indicator that could be used to give the end point. 1 MARK

c. Calculate the amount of iodine used in the titration. 1 MARK

d. Calculate the concentration of sulfur dioxide in the diluted wine sample. 2 MARKS

e. Determine the dilution factor. 1 MARK

f. Calculate the concentration of sulfur dioxide in the original (undiluted) wine. 1 MARK

Question 12 (5 MARKS)

Ethanedioic acid (oxalic acid), $H_2C_2O_4$, can be used as a protective layer on marble sculptures to preserve the integrity of the structure. Ethanedioic acid can take part in titration reactions with an acidified solution of potassium permanganate, $KMnO_4$, resulting in an exothermic reaction according to the following equation.

$$MnO_4^-(aq) + \frac{5}{2}C_2O_4^{2-}(aq) + 8H^+(aq) \rightarrow Mn^{2+}(aq) + 5CO_2(aq) + 4H_2O(l)$$

In a titration between these two substances, it was found that an average of 18.95 mL of a 0.500 M solution of potassium permanganate was required to reach the end point.

a. Given that an aliquot of 25.00 mL was used, determine the concentration, in M, of the ethanedioic acid solution sample. 3 MARKS

b. In a different experiment the ethanedioic acid aliquot was taken from 1.00 L of a 1.1 M ethanedioic acid solution. Determine the mass of ethanedioic used to produce this solution. 2 MARKS

Question 13 (7 MARKS)

It was found that 14.55 mL of a 0.500 M solution of $KMnO_4$ was required to fully oxidise a 20.0 mL sample of $FeSO_4$ to Fe^{3+} ions in an acidic solution.

a. Write a balanced redox half-equation for the reduction of permanganate ions to manganese ions, Mn^{2+}. 2 MARKS

b. Determine the concentration, in mol L^{-1}, of the $FeSO_4$ solution. 3 MARKS

c. The $FeSO_4$ aliquot used in the reaction was transferred from a 250.0 mL flask that was originally made from a 25.0 mL solution of concentrated $FeSO_4$. Determine the concentration, in mol L^{-1}, of the original sample of $FeSO_4$. 2 MARKS

Question 14 🌶🌶🌶 (11 MARKS)

A student was asked to design a series of tests to deduce the identity of the following organic liquids:

I. Propan-1-ol

II. Pent-1-ene

III. Cyclohexane

a. Explain how the identity of propan-1-ol can be deduced. Include the following in your answer: 3 MARKS

- outline of the test
- the chemicals required
- expected observation.

b. Explain how the identity of pent-1-ene can be deduced. Include the following in your answer: 4 MARKS

- the type of reaction
- an appropriate chemical equation
- outline of the test
- expected observation.

c. Explain how the identity of cyclohexane can be deduced. Include the expected observations in your answer. 2 MARKS

d. Explain why is it not recommended to use either potassium permanganate or dichromate to differentiate between the alcohol and alkene. 2 MARKS

Key science skills (10 MARKS)

Question 15 🌶🌶 (10 MARKS)

Permanganate ions can be used to detect the presence of hydrogen peroxide. In order to do this, hydrogen peroxide, H_2O_2, is titrated with potassium permanganate, $KMnO_4$, during which hydrogen peroxide is oxidised to $O_2(g)$ by permanganate ions, MnO_4^-, and the permanganate ion is reduced to the Mn^{2+} ion. Due to the changes in oxidation state of the manganese ion, a colour change can be observed as a result of the reaction.

a. Write a balanced overall redox equation for this reaction. 2 MARKS

b. How could the observer tell from a titration curve that the permanganate ions underwent a redox reaction and not an acid-base reaction? 1 MARK

c. In an experiment, a student used 12.00 mL of a 1.50 g L^{-1} solution of potassium permanganate to titrate against a 20.00 mL aliquot of hydrogen peroxide. Determine the concentration of the hydrogen peroxide solution in mol L^{-1}. 5 MARKS

d. Hydrogen peroxide can cause severe burns and eye damage. Identify two safety considerations when handling hydrogen peroxide. 2 MARKS

FROM LESSONS 12B, 12C & 12E

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10

CHAPTER 10

Instrumental analysis of organic compounds

LESSONS

10A Mass spectrometry

10B Infrared spectroscopy

10C Low resolution carbon-13 nuclear magnetic resonance spectroscopy

10D Low and high resolution proton nuclear magnetic resonance spectroscopy

10E Chromatography

10F Combining techniques

Chapter 10 review

KEY KNOWLEDGE

- applications of mass spectrometry (excluding features of instrumentation and operation) and interpretation of qualitative and quantitative data, including identification of molecular ion peak, determination of molecular mass and identification of simple fragments
- identification of bond types by qualitative infrared spectroscopy (IR) data analysis using characteristic absorption bands
- structural determination of organic compounds by low resolution carbon-13 nuclear magnetic resonance (^{13}C-NMR) spectral analysis, using chemical shift values to deduce the number and nature of different carbon environments
- structural determination of organic compounds by low and high resolution proton nuclear magnetic resonance (^{1}H-NMR) spectral analysis, using chemical shift values, integration curves (where the height is proportional to the area underneath a peak) and peak splitting patterns (excluding coupling constants), and application of the n + 1 rule (where n is the number of neighbouring protons) to deduce the number and nature of different proton environments
- the principles of chromatography, including high performance liquid chromatography (HPLC) and the use of retention times and the construction of a calibration curve to determine the concentration of an organic compound in a solution (excluding features of instrumentation and operation)
- deduction of the structures of simple organic compounds using a combination of mass spectrometry (MS), infrared spectroscopy (IR), proton nuclear magnetic resonance (^{1}H-NMR) and carbon-13 nuclear magnetic resonance (^{13}C-NMR) (limited to data analysis)
- the roles and applications of laboratory and instrumental analysis, with reference to product purity and the identification of organic compounds or functional groups in isolation or within a mixture

Image: smereka/Shutterstock.com

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10A Mass spectrometry

STUDY DESIGN DOT POINT

- applications of mass spectrometry (excluding features of instrumentation and operation) and interpretation of qualitative and quantitative data, including identification of molecular ion peak, determination of molecular mass and identification of simple fragments

10A 10B 10C 10D 10E 10F

4.2.5.1 & 4.2.5.2 Mass spectrometry & analysing mass spectra

ESSENTIAL PRIOR KNOWLEDGE

- Relative atomic mass
- Isotopes

See questions 78–79.

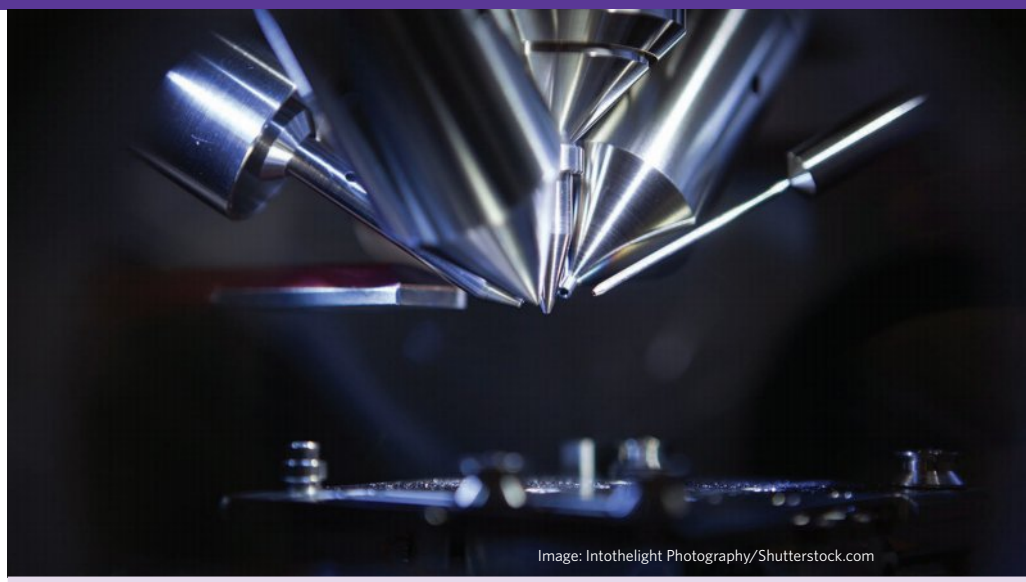


Image: Intothelight Photography/Shutterstock.com

How is mass spectrometry used to detect diseases?

Time-of-flight mass spectrometers – which have evolved from basic mass spectrometers – are sensitive analytical machines that can be used to screen for markers of disease in biological samples. In this lesson, we will learn about the information provided by basic **mass spectrometry**, and how we can interpret mass spectra of molecular compounds.

KEY TERMS AND DEFINITIONS

Base peak the most intense peak in a mass spectrum, which is assigned a relative abundance of 100%

Fragment ion simple positively charged fragment formed from the cleavage of bonds in the molecular ion

Fragmentation the process in which molecular ions undergo bond cleavage to form smaller fragments

Mass/charge ratio (*m/z*) the ratio of the mass of an ion relative to its charge

Mass spectrometry analytical technique used to measure the mass-to-charge ratio of ions in a sample

Molecular ion the ion formed when a neutral molecule is bombarded with high-energy electrons

Molecular (parent) ion peak the peak in the mass spectrum that corresponds to the molecular ion, which has the highest *m/z* ratio

Relative abundance the abundance/intensity of an ion relative to the base peak

Mass spectrometry & analysing mass spectra 4.2.5.1 & 4.2.5.2

Mass spectrometry is an analytical technique used to determine the relative masses of molecules.

How is mass spectrometry used to determine the relative masses of molecules?

A mass spectrometer generates and detects positively charged ions (**molecular ions** and **fragment ions**) from the original molecular element or compound.

A sample of molecules is bombarded by high-energy electrons, forming a number of mainly singly charged positive ions. The molecules undergo **fragmentation**, forming smaller positively charged ion fragments. The paths of these fragments through a magnetic field are detected in a mass spectrometer (figure 1).[1]

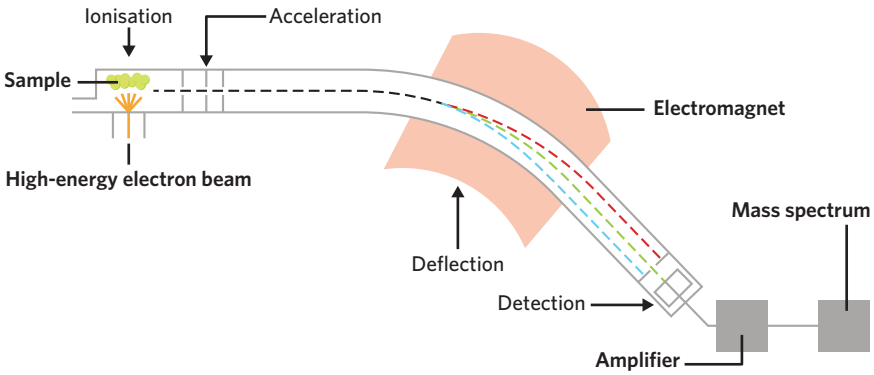


Figure 1 Diagram of a mass spectrometer

The output is a mass spectrum, which plots the **mass/charge ratio (m/z)** against the **relative abundance** of each fragment. For example, the mass spectrum for a sample of pure ethanal, CH_3CHO, molecules is shown in figure 2.

KEEN TO INVESTIGATE?

[1] **How does a mass spectrometer actually work?**
Search YouTube:
Mass Spectrometry MS RSC

USEFUL TIP

For the purposes of the VCE study design, the principles of the mass spectrometry process are not required knowledge.

MISCONCEPTION

'Neutral species or fragments can be detected in a mass spectrometer.'

Only fragments or species that are positively charged can be detected in this type of mass spectrometry.

USEFUL TIP

A mass spectrum can have either relative abundance or relative intensity on the vertical axis. For the purposes of mass spectrometry in VCE chemistry, abundance and intensity can be considered as interchangeable terms.

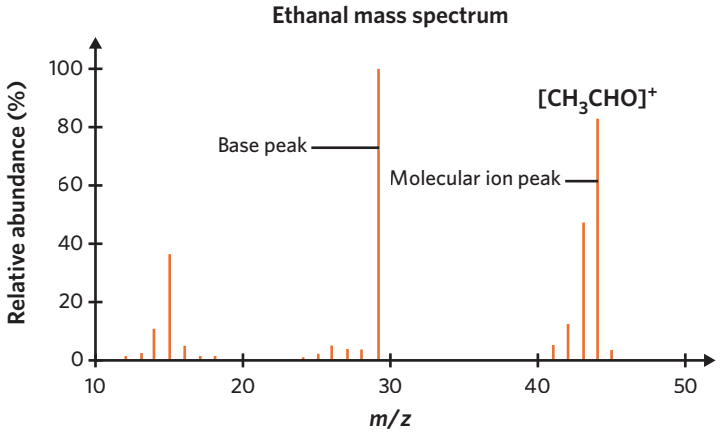


Figure 2 Mass spectrum of ethanal

As shown in figure 2, the peak of the most abundant ion is assigned a relative abundance of 100% – this is known as the **base peak**. The peak with the highest m/z ratio is known as the **molecular (parent) ion peak**. The m/z ratio of the molecular ion peak represents the relative mass of the original unfragmented molecule being analysed. In the initial ionisation stage, the molecular ion is bombarded with high-energy electrons, causing it to lose an electron, which in turn gives it a positive charge. The formation of the molecular ion is given by the following equation.

$M(g) + e^- \rightarrow [M]^+(g) + 2e^-$ where $[M]^+$ denotes the molecular ion

By identifying the molecular ion peak on a mass spectrum, we can determine the m/z charge ratio of the molecular ion. Since the molecular ion usually has a charge of +1, we can assume that $z = 1$. Therefore, the molecular mass of the original unfragmented molecule is equivalent to the m/z charge ratio of the molecular ion peak. In figure 2, the molecular ion peak has a m/z ratio of approximately 44.

USEFUL TIP

In the Edrolo VCE chemistry textbook, molecular ions and fragments will always be represented as $[M]^+$, as the brackets [ ] indicate that the positive charge is spread across the whole molecule, instead of being applicable to just one atom.

MISCONCEPTION

'The molecular ion can only have a charge of +1.'

Many of the examples in VCE chemistry deal only with molecular ions with a charge of +1. However, the molecular ion can in fact take any positive charge. The charge of the molecular ion depends on the number of electrons lost during the ionisation stage of mass spectrometry.

Hence, the molecular mass of $[CH_3CHO]^+$ is calculated as shown:

$$M([CH_3CHO]^+) = \frac{\text{mass}}{\text{charge}}$$

$$M([CH_3CHO]^+) = \frac{44 \text{ g mol}^{-1}}{1}$$

$$M([CH_3CHO]^+) = 44 \text{ g mol}^{-1}$$

In a mass spectrum, the smaller peaks surrounding a large peak are often caused by ions containing isotopes of the elements in the ion responsible for the large peak. For example, in the mass spectrum of propanoic acid (CH_3CH_2COOH, $M = 74.0$ g mol^{-1}) shown in figure 3, we can see a peak with an m/z ratio of 74 and a peak with an m/z ratio of 75. The peak at 75 m/z is likely to be caused by molecular ions of propanoic acid containing the ^{13}C isotope.

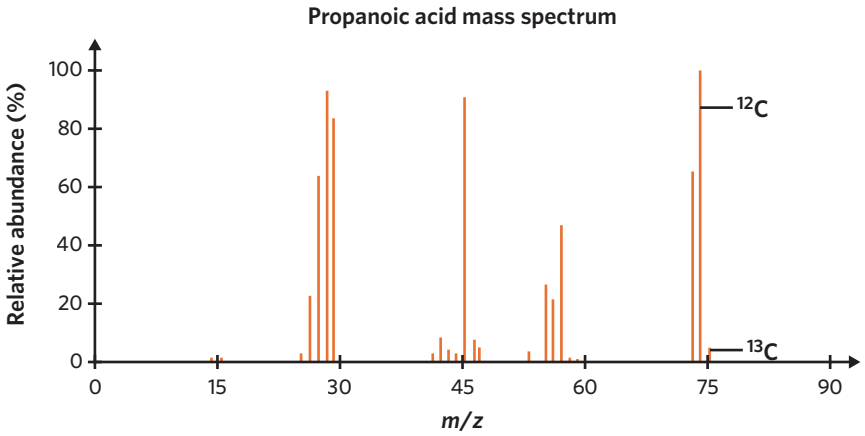


Figure 3 Mass spectrum of propanoic acid

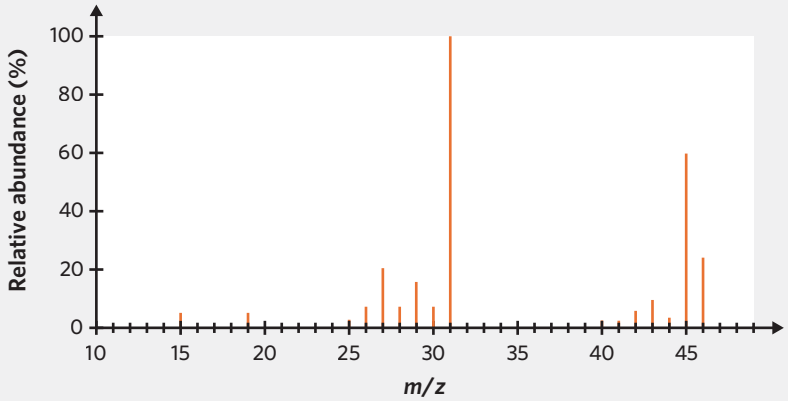
USEFUL TIP

In some cases, the most abundant ion will also be the ion with the highest m/z ratio in the sample, meaning the base peak will also be the molecular ion peak.

Although the peak at 75 m/z corresponds to the ion with the greatest molecular mass, when we have a cluster of peaks we take the molecular ion peak to be the peak with the highest relative abundance. Hence, in figure 3, the molecular (parent) ion peak would be the peak at 74 m/z, which corresponds to the molecular ion $[CH_3CH_2COOH]^+$.

WORKED EXAMPLE 1

The mass spectrum of ethanol, C_2H_5OH, is given.



What fragment must have been lost from the molecular ion to account for the high peak at m/z 45.0?

What information is presented in the question?

The mass spectrum of ethanol.

What is the question asking us to do?

Determine the fragment lost from the molecular ion to account for the high peak at m/z 45.0.

Continues →

What strategies do we need in order to answer the question?

1. Determine the formula of the molecular ion.
2. Determine the molecular mass of the molecular ion.
3. Determine which atom or combination of atoms must have been lost based on their relative masses.

Answer

The molecular ion is a molecule of ethanol with a +1 charge. Hence, the formula of the molecular ion is $[C_2H_6O]^+$.

$M([C_2H_6O]^+) = (2 \times 12.0 \text{ g mol}^{-1}) + (6 \times 1.0 \text{ g mol}^{-1}) + 16.0 \text{ g mol}^{-1}$

$M([C_2H_6O]^+) = 46.0 \text{ g mol}^{-1}$

Therefore, the molecular ion must have lost a fragment with a relative mass of 1.0 g mol^{-1}. Only the H atom or the H^+ ion have relative masses of 1.0 g mol^{-1}. However, for the fragment responsible for the peak at m/z 45.0 to actually appear on the mass spectrum, it must be charged. Hence, the molecular ion could not have lost a H^+ ion as it would become neutral. Therefore, the fragment that must have been lost from the molecular ion to account for the high peak at m/z 45.0 is a hydrogen atom, H.

VCAA 2008 Exam 1 Short answer Q7d

How is mass spectrometry used to determine the relative masses of fragments?

Fragmentation occurs when bonds within the molecular ion are cleaved, resulting in the formation of smaller fragment ions. The following equation shows the formation of the fragment ion $[X]^+$ from the molecular ion.

$[M]^+ \rightarrow [X]^+ + R^\bullet$

To identify simple fragments, we need to:

1. Analyse the mass spectrum to identify any peaks with lower m/z values than the molecular ion.
2. Determine the m/z values of these peaks, and hence, the corresponding fragment masses.

Consider the mass spectrum of ethanoic acid, CH_3COOH, shown in figure 4.

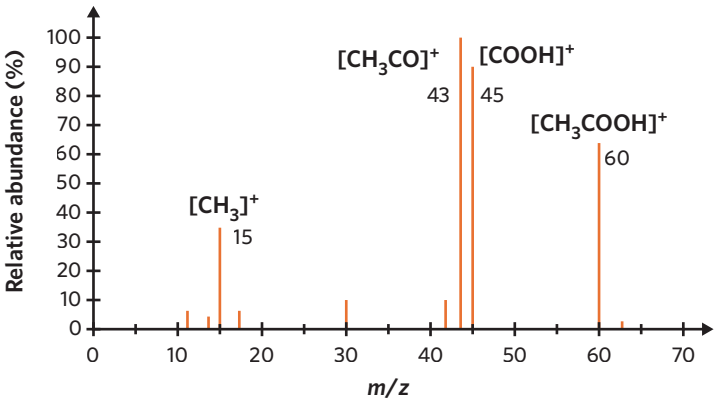


Figure 4 Mass spectrum of ethanoic acid

In figure 4, the molecular ion is $[CH_3COOH]^+$ as it is the ion with the highest m/z ratio. We can also see several other discernible peaks that correspond to the ion fragments formed.

For example, the base peak (the peak with a relative abundance of 100%) is formed by $[CH_3CO]^+$, which has a m/z ratio of 43, and hence, a relative mass of 43 g mol^{-1}.

There is also a peak at 15 m/z, which is formed by $[CH_3]^+$, one of the more common fragmented ions in mass spectra of organic compounds. From this, we can conclude that $[CH_3]^+$ has a molecular mass of 15 g mol^{-1}. Table 1 provides the mass/charge ratios of several ions that are commonly formed in the fragmentation of organic molecular ions.

USEFUL TIP

In the fragmentation equation, $R^\bullet$ symbolises an alkyl group with an unpaired electron ($^\bullet$). This is known as a free radical, which is not within the scope of the VCE chemistry study design.

Table 1 m/z ratios of common fragmented ions

Formula	m/z
$[CH_3]^+$	15
$[OH]^+$	17
$[CH_3CH_2]^+$, $[COH]^+$	29
$[CH_3O]^+$	31
$^{35}Cl^+$	35
$^{37}Cl^+$	37
$[CH_3CH_2CH_2]^+$, $[CH_3CO]^+$	43
$[COOH]^+$	45
$^{79}Br^+$	79
$^{81}Br^+$	81

USEFUL TIP

Bonds involving oxygen atoms are commonly broken in the mass spectrometer due to the high electronegativity of oxygen, which draws electrons away from other atoms that are bonded to it.
This makes these bonds weaker and more susceptible to being broken by high-energy electrons.

USEFUL TIP

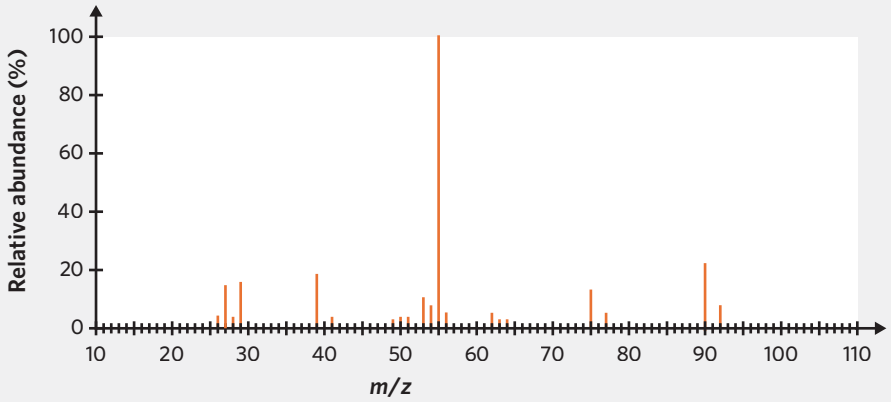
Unless stated otherwise, molecular ions and fragments can be represented in several forms. For example, the molecular ion of ethyl butanoate, $CH_3CH_2CH_2COOCH_2CH_3$, can be written as:

- $[CH_3CH_2CH_2COOCH_2CH_3]^+$
- $CH_3CH_2CH_2COOCH_2CH_3^+$
- $[C_6H_{12}O_2]^+$
- $C_6H_{12}O_2^+$

These forms are all acceptable in VCE chemistry.

WORKED EXAMPLE 2

The mass spectrum for a molecule with the molecular formula C_4H_7Cl is shown.



Which species is responsible for the base peak?

A. $[C_4H_7Cl]^+$ **B.** $[C_3H_4Cl]^+$ **C.** $[C_3H_5]^+$ **D.** $[C_4H_7]^+$

What information is presented in the question?

The mass spectrum for a molecule with the molecular formula C_4H_7Cl.

What is the question asking us to do?

Determine which species is responsible for the base peak.

What strategies do we need in order to answer the question?

1. Identify the base peak, i.e. the peak with a relative abundance of 100%.
2. Determine the m/z ratio and hence the relative mass of the species responsible for the base peak.
3. Compare this relative mass to the relative mass of the different species given in the question.

Answer

From the mass spectrum, the base peak is the peak with a m/z ratio of 55.0. Given each option provided has a charge of +1, we know that $z = 1$ for the species responsible for the base peak, so the species has a relative mass of 55.0 g mol^{-1}. Now we can calculate the relative mass of the species given in each option.

Option A: $M(C_4H_7Cl^+) = (4 \times 12.0 \text{ g mol}^{-1}) + (7 \times 1.0 \text{ g mol}^{-1}) + 35.5 \text{ g mol}^{-1}$

$M(C_4H_7Cl^+) = 90.5 \text{ g mol}^{-1}$

Option B: $M(C_3H_4Cl^+) = (3 \times 12.0 \text{ g mol}^{-1}) + (4 \times 1.0 \text{ g mol}^{-1}) + 35.5 \text{ g mol}^{-1}$

$M(C_3H_4Cl^+) = 75.5 \text{ g mol}^{-1}$

Option C: $M(C_3H_5^+) = (3 \times 12.0 \text{ g mol}^{-1}) + (5 \times 1.0 \text{ g mol}^{-1})$

$M(C_3H_5^+) = 41.0 \text{ g mol}^{-1}$

Option D: $M(C_4H_7^+) = (4 \times 12.0 \text{ g mol}^{-1}) + (7 \times 1.0 \text{ g mol}^{-1})$

$M(C_4H_7^+) = 55.0 \text{ g mol}^{-1}$

Since the relative mass of $[C_4H_7]^+$ aligns with the relative mass of the species responsible for the base peak in the mass spectra, the correct answer is D.

Adapted from VCAA (NHT) 2018 exam Multiple choice Q23

How is mass spectrometry applied in the real world?

The key results obtained from mass spectrometry can be both qualitative and quantitative. In some cases, we want to screen for a certain molecule of known molecular mass in a sample; this is a qualitative analysis for the presence of the molecule. In other cases, we are interested in determining the molecular mass of the molecules in a sample: a quantitative analysis.

Mass spectrometry has a number of applications in industrial chemistry, such as in environmental analysis. Namely, it is used in the testing of drinking water, as well as in the screening and quantification of pesticides in crops and soils. Mass spectrometry is also a key analytical tool in pharmaceutical analysis and clinical drug development, such as in the identification of infectious agents.

However, there are a number of disadvantages involved with the use of mass spectrometry as an analytical technique. These disadvantages include:

- Mass spectrometry requires pure samples.
- Mass spectrometry does not offer direct structural information; it only provides molecular mass.
- Mass spectrometry is not suitable for non-volatile compounds, i.e. compounds that do not ionise easily.
- Mass spectrometry is a destructive technique, meaning the sample cannot be recovered.

For these reasons, laboratories will carry out several other analytical techniques, such as infrared spectroscopy (lesson 10B), before carrying out mass spectrometry as the sample will then be destroyed. Some processes now forego mass spectrometry entirely, opting instead for non-destructive techniques to determine the relative mass of molecules.

PROGRESS QUESTIONS

Question 1

Which information can be obtained from the mass-to-charge ratio (m/z) in a mass spectrum?

A. The molecular mass of the compound

B. The number of carbon atoms in the compound

C. The compound's solubility in water

D. The compound's boiling point

Question 2

The molecular ion peak is produced by

A. a negatively charged ion.

B. the ionisation of the parent molecule.

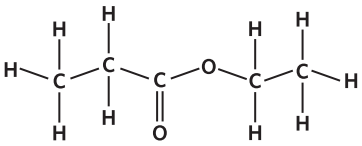
C. a fragment.

D. a neutral compound.

Continues →

Question 3

Consider the structure shown.



The species that produces the molecular ion peak in the mass spectrum of this compound is

A. $[CH_3CH_2COOCH_2CH_3]^+$

B. $[CH_3CH_2COOCH_2CH_3]^{2+}$

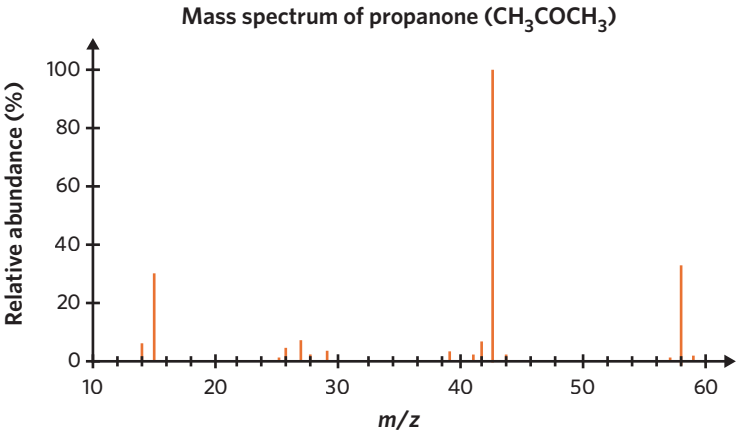
C. $[CH_3CH_2COOCH_2CH_3]^-$

D. $CH_3CH_2COOCH_2CH_3$

VCAA 2012 Exam 1 Multiple choice Q10

Use the following mass spectrum to answer questions 4–5.

Consider the mass spectrum for propanone.



Question 4

Which species is responsible for the peak at $m/z = 58$?

A. CH_3CO **B.** $[CH_3CO]^+$ **C.** CH_3COCH_3 **D.** $[CH_3COCH_3]^+$

Question 5

Which of the following fragments could be responsible for the peak at $m/z = 15$?

A. $[CH_3]^+$ **B.** $[CH_3]^{2+}$ **C.** $[CH_3CO]^+$ **D.** $[CH_3CO]^{2+}$

Question 6

In mass spectrometry, what does the term 'qualitative analysis' refer to?

A. Determining the relative abundance of isotopes

B. Determining the boiling point of a compound

C. Identifying the presence of specific ions or fragments

D. Measuring the concentration of a compound

Theory summary

- When ionisation occurs in mass spectrometry, molecules are bombarded with high-energy electrons, forming molecular ions.
  - $M(g) + e^- \rightarrow [M]^+(g) + 2e^-$ where $[M]^+$ denotes the molecular ion.
- Fragmentation of molecular ions results in the formation of simpler fragment ions.
  - $[M]^+(g) \rightarrow [X]^+(g) + R^\bullet(g)$ where $[X]^+$ denotes a fragment ion.
- A mass spectrum plots the mass/charge ratio of positively charged ions (normally +1) against the relative abundance (or relative intensity) of those ions.
- The base peak is the peak assigned a relative abundance of 100% on a mass spectrum.
- The molecular (parent) ion peak is the peak with the highest m/z ratio on a mass spectrum.
- The m/z ratio of an ion can be used to determine its molecular mass, M.
  - $M = \frac{\text{mass}}{\text{charge}}$
- The smaller peaks surrounding a large peak are caused by ions containing isotopes of elements.
- On a mass spectrum, the peaks caused by simple fragments are those with lower m/z values than that of the molecular ion.

10A Questions

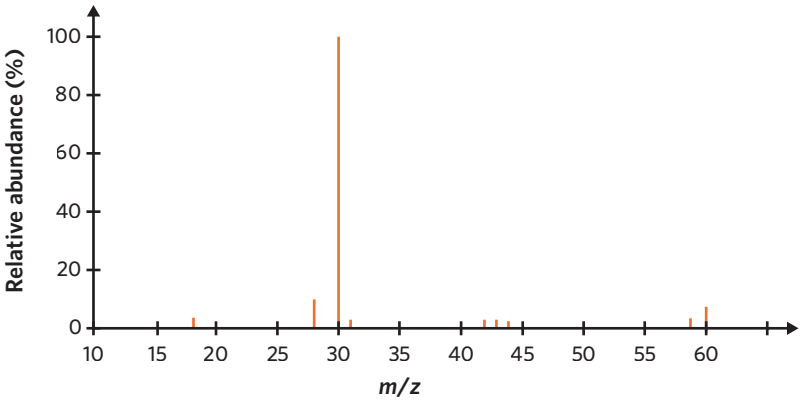
Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

A bottle containing an unknown organic compound was examined in a university laboratory. There was an incomplete label on the bottle that gave only the empirical formula for the contents: CH_4N. A chemist hypothesised that the unknown compound was 1,2-ethanediamine, $NH_2CH_2CH_2NH_2$.

Mass spectrometry produced the following spectral data.



Question 7 (1 MARK)

The m/z ratio of the base peak is

A. 15 **B.** 28 **C.** 30 **D.** 60

Adapted from VCAA 2016 exam Short answer Q4ai

Question 8 (1 MARK)

At what m/z ratio is the principal peak that supports the chemist's hypothesis that the unknown compound has the formula $NH_2CH_2CH_2NH_2$?

A. 15 **B.** 28 **C.** 30 **D.** 60

Adapted from VCAA 2016 exam Short answer Q4aii

Question 9 (1 MARK)

Write the semi-structural formula of the species that produces the peak at 30 m/z.

Adapted from VCAA 2016 exam Short answer Q4aiii

Exam-style

Question 10 (3 MARKS)

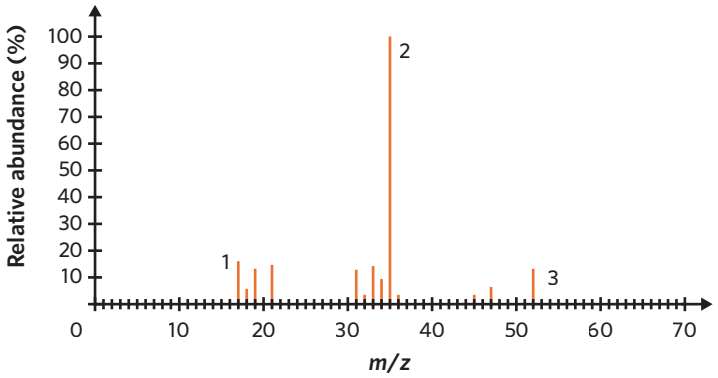
A sample of compound T is analysed in a mass spectrometer, where it forms the molecular ion T^+.
The molecular ion fragments according to the following equations.

$[T]^+ \rightarrow [A]^+ + B^\bullet$

$[T]^+ \rightarrow A^\bullet + [B]^+$

a. Which of the species given in the equations would be visible as peaks in a mass spectrum? 1 MARK

b. Consider the mass spectrum shown.

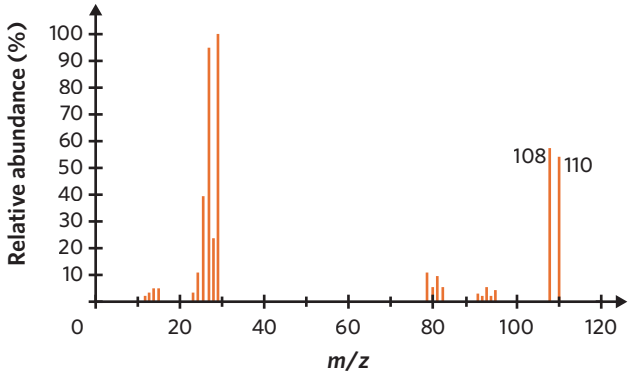


i. It is known that A has a higher relative mass than B. Identify which species is responsible for each of the peaks labelled 1, 2, and 3 on the mass spectrum. 1 MARK

ii. Which of these peaks is the base peak? 1 MARK

Question 11 (3 MARKS)

Bromine exists as two isotopes, ^{79}Br and ^{81}Br. The mass spectrum of bromoethane, C_2H_5Br, with two molecular ion peaks at m/z 108 and 110, is shown.



a. Identify the species that produces the peak at $m/z = 29$. 1 MARK

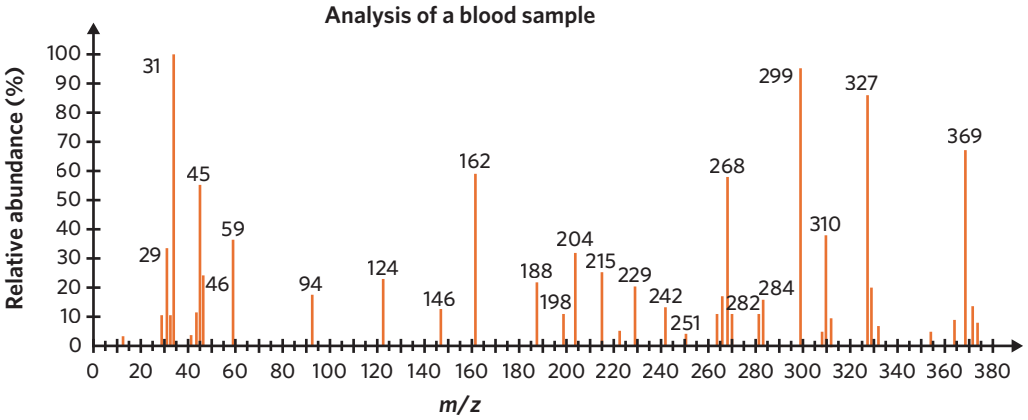
b. What do the two molecular ion peaks indicate about the relative abundance of ^{79}Br and ^{81}Br? Give a reason for your answer. 2 MARKS

VCAA 2011 Exam 1 Short answer Q2a

Key science skills

Question 12 (8 MARKS)

Mossem is a company that carries out clinical studies to test newly developed medications on human patients. Before trials can begin, Mossem must ensure that all patients are valid test subjects, and to do so, they screen for and remove applicants who regularly ingest certain compounds. A mass spectrum of a blood sample obtained during the screening process is shown.



Also given is a table containing the m/z ratios of fragments contained in some of the compounds that Mossem screens for.

Compound name	Nicotine	Codeine	Ethanol
***m/z* ratios of significant fragments**	42, 84, 133, 162	188, 229, 299	29, 31, 45, 46

a. Which of the substances listed in the table might be present in the blood sample according to the mass spectrum? Explain your answer. 3 MARKS

b. What effect does the screening process have on the validity of the results obtained from clinical studies? 2 MARKS

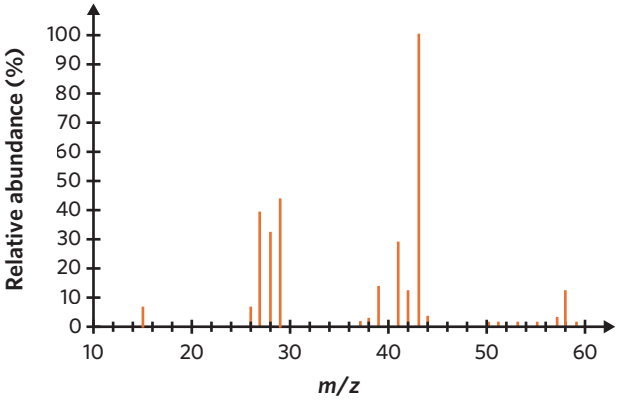
c. Codeine is a compound used to relieve pain, and is also used by people with colds to reduce coughing. Discuss the ethical considerations regarding Mossem's exclusion of patients whose blood samples contain codeine. 3 MARKS

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

Question 13 (3 MARKS)

The mass spectrum of an unbranched alkane is shown.



The molecular ion has a charge of +1. Use the mass spectrum to identify the IUPAC name of the unbranched alkane. Justify your answer.

FROM LESSON 7A

Back to contents

10B Infrared spectroscopy

STUDY DESIGN DOT POINT

- identification of bond types by qualitative infrared spectroscopy (IR) data analysis using characteristic absorption bands

10A 10B 10C 10D 10E 10F

4.2.6.1 & 4.2.6.2 Infrared spectroscopy & analysing infrared spectra

ESSENTIAL PRIOR KNOWLEDGE

7A Functional groups

See question 80.



Image: Daniel Chetroni/Shutterstock.com

How is infrared spectroscopy used to keep our roads safer?

Breathalysers used in roadside breath tests contain compact infrared spectrometers that can detect the level of ethanol (alcohol) in the breath. In this lesson, we will learn how to analyse an **infrared spectrum** produced from infrared spectrometers to identify the types of bonds and functional groups present in organic compounds.

KEY TERMS AND DEFINITIONS

Absorbance measure of the amount of light that is absorbed by a substance

Fingerprint region complex absorption pattern in the region between 400 cm^{-1} and 1500 cm^{-1} that is unique to each organic compound

Infrared light invisible electromagnetic radiation that transmits energy

Infrared spectroscopy qualitative analytical technique that uses infrared radiation to analyse the bond vibrations, providing information about molecular structures and functional groups

Infrared spectrum graph representing the absorbance of infrared light at different wavelengths within the infrared region of the electromagnetic spectrum

Transmittance measure of the amount of light that passes through a substance

Wave number the reciprocal of the wavelength of light measured in cm^{-1}

Infrared spectroscopy & analysing infrared spectra 4.2.6.1 & 4.2.6.2

Infrared spectroscopy is a qualitative analytical technique used to identify the types of bonds and functional groups present in an organic molecule.

How is infrared spectroscopy used to identify bond types?

In most depictions seen in VCE chemistry, bonds between atoms in a molecule appear static. In reality, these bonds are actually vibrating backwards and forwards, which results in the bonds bending and stretching (figure 1).

Infrared light is a type of electromagnetic radiation that is transmitted through empty space or matter as waves. Like all waves in the electromagnetic spectrum, infrared waves transmit energy, and when organic molecules are exposed to infrared (IR) light, the bonds between atoms absorb this energy.[1] With the right wavelength of IR light, the frequency of bond vibrations can be increased to the point where the bonds increase the amount of bending and stretching that occurs.

Since each bond type absorbs IR light at a unique, characteristic wavelength, the amount of energy absorbed at different wavelengths can be measured to identify the bond types, and hence the functional groups, present in a molecule. This is done through infrared spectroscopy.

In IR spectroscopy, an organic molecule is exposed to infrared light at various wavelengths and an IR spectrum is produced (figure 2). IR specta graph **transmittance** (%), the opposite of **absorbance**, against **wave number** (cm^{-1}), the inverse of wavelength.

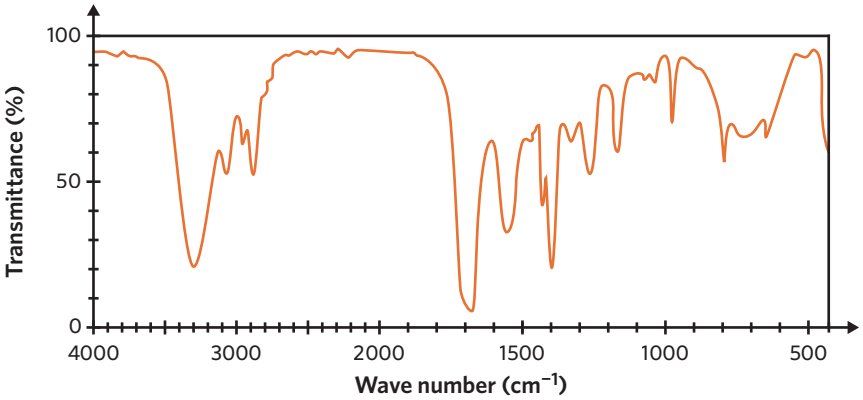


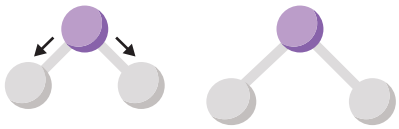
Figure 2 An infrared spectrum

In figure 2, there are several distinct peaks in absorbance (or troughs in transmittance) on the IR spectrum. A peak present at a particular wavelength tells us that there is a bond present in the compound that absorbs infrared light at that wavelength. In an infrared spectrometer, this absorption of infrared light is not determined by measuring the amount of light that is absorbed, but rather the amount of infrared light that is transmitted. The wave numbers at which the peaks on an IR spectrum occur can be compared with the characteristic ranges for infrared absorption provided in the VCE Data Book (table 1) to identify the bond responsible for the peak.

Table 1 Characteristic ranges for infrared absorption

Bond	Wave number (cm^{-1})
C–Cl (chloroalkanes)	600–800
C–O (alcohols, esters, ethers)	1050–1410
C=C (alkenes)	1620–1680
C=O (amides)	1630–1680
C=O (aldehydes)	1660–1745
C=O (acids)	1680–1740
C=O (ketones)	1680–1850
C=O (esters)	1720–1840
C–H (alkanes, alkenes, arenes)	2850–3090
O–H (acids)	2500–3500
O–H (alcohols)	3200–3600
N–H (amines and amides)	3300–3500

Stretching



Bending

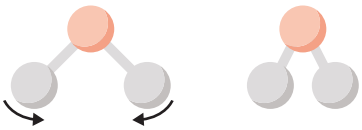


Figure 1 Stretching and bending of atoms increases when a particular wavelength of light is absorbed.

KEEN TO INVESTIGATE?

1 **How did William Herschel discover infrared light?**
Search YouTube: Neil deGrasse Tyson: The Brilliant Way Ultraviolet & Infrared Light Was Discovered

USEFUL TIP

In IR spectroscopy, we are actually interested in the % absorbance of different bond types, so we describe the troughs in transmittance as peaks in absorbance, or simply as peaks.

USEFUL TIP

In VCE chemistry, for questions asking you to identify the bonds in a molecule from an infrared spectrum, you must state both the bond and the type of organic compound, e.g C=O (esters). For instance, the carbonyl bond, C=O, is part of five different functional groups, so it is very important to identify the functional group it is part of.

From table 1, we can see that many of the characteristic absorption ranges overlap, making it difficult to determine which bond type is responsible for a peak on an IR spectrum. Therefore, it helps to be able to distinguish between bond types based on the typical shape and strength of the peaks (figure 3).

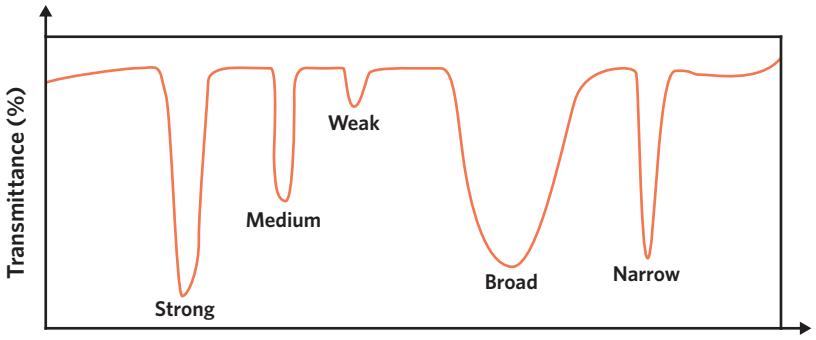


Figure 3 Different shapes and strengths of peaks in an IR spectrum

Table 2 lists the typical shape and/or strength of the peaks caused by some of the bond types listed in table 1.

Table 2 Shape and strength of bond types

Bond	Wave number (cm^{-1})	Type of peak
C–O (alcohols, esters, ethers)	1050–1410	Strong
C=C (alkenes)	1620–1680	Medium
C=O (amides)	1630–1680	Strong
C=O (aldehydes)	1660–1745	Strong
C=O (acids)	1680–1740	Strong
C=O (ketones)	1680–1850	Strong
C–H (alkanes, alkenes, arenes)	2850–3090	Medium
O–H (acids)	2500–3500	Strong, broad
O–H (alcohols)	3200–3600	Strong, broad (narrower than O–H (acid) peak)
N–H (amines and amides)	3300–3500	Medium, broad

Figure 4 shows the same IR spectrum as in figure 2, but with a few additional features. Firstly, there are three arrows pointing to the three distinct peaks at wave numbers of approximately 3300 cm^{-1}, 3070 cm^{-1}, and 1670 cm^{-1}. There is also the **fingerprint region** from 400 cm^{-1} to 1500 cm^{-1}, which is unique for all molecules. From table 1, the wave numbers of IR light absorbed by C–Cl and C–O bonds are included in the fingerprint region.

MISCONCEPTION

'An IR spectrum cannot be used to assess the purity of a sample.'

Every pure compound has a unique fingerprint region on its IR spectrum, so by comparing the fingerprint region of the sample with the fingerprint region of the pure compound, we can qualitatively assess the purity of a sample.

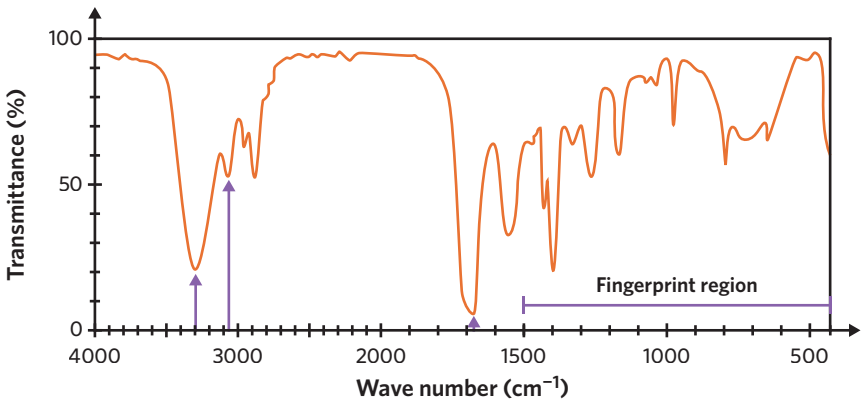


Figure 4 Identifying the peaks and fingerprint region of an infrared spectrum

Now that we have identified the three clear peaks in the spectrum, we can use the characteristic ranges provided in table 1 and the typical shapes and strengths provided in table 2 to identify the bond types present in the organic molecule (figure 5).

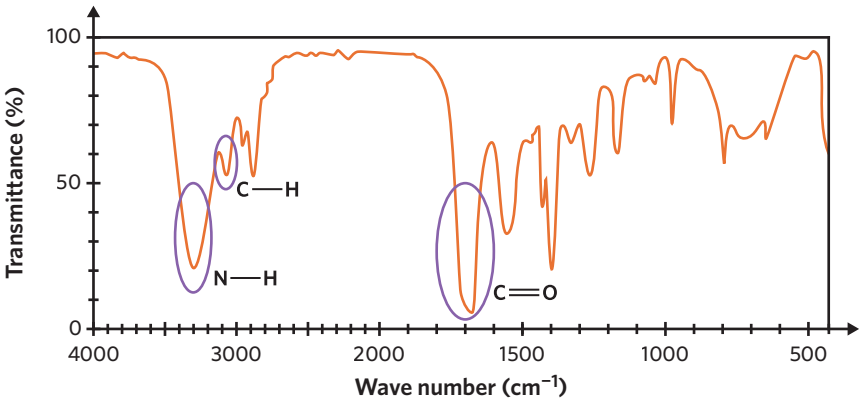


Figure 5 Identifying the bond types present in an organic molecule

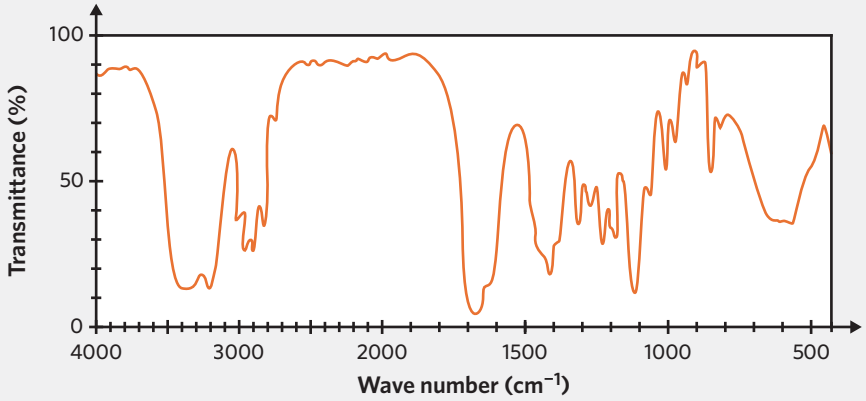
From table 1, the peak at 3300 cm^{-1} could correspond to either an O—H bond in an alcohol, an O—H bond in an acid, or an N—H bond in an amine or amide. From table 2, the shape of the peak at 3300 cm^{-1} best matches the description of an N—H bond, which is medium and broad. The peak at 3070 cm^{-1} is best described as being of medium strength, and so using the information presented in tables 1 and 2, this peak is caused by a C—H bond. From table 1, the peak at 1670 cm^{-1} could be caused by a C=C bond or a C=O bond. However, table 2 tells us that a strong peak at 1670 cm^{-1} must be caused by a C=O bond.

USEFUL TIP

It is important to read questions carefully to determine whether the type of organic compound or name of the functional group is required.

WORKED EXAMPLE 1

The infra-red (IR) spectrum of an organic compound is shown below.



Referring to the IR spectrum, the compound could be

A. $CH_3CH_2COOCH_3$ **B.** $CH_3CH_2CH_2CHO$

C. $NH_2CH_2CH_2CONH_2$ **D.** $NH_2CH_2CH_2CH(OH)CH_3$

What information is presented in the question?

The IR spectrum of an organic compound.

What is the question asking us to do?

Determine which compound corresponds to the IR spectrum shown.

What strategies do we need in order to answer the question?

1. Identify the peaks in the mass spectrum.
2. Use the VCE Data Book to identify which bond types could be responsible for each peak.
3. Compare the bond types present in the compound with each option.

Continues →

Answer

The IR spectrum has three peaks at approximately 3400 cm^{-1}, 2900 cm^{-1}, and 1660 cm^{-1}. Using the characteristic ranges for infra-red absorption from the VCE Data Book, the first (leftmost) peak on the spectrum lies in the absorption range for N—H and O—H (alcohols and acids) bonds. The second peak lies in the absorption range of C—H and O—H (acids) bonds. The third peak lies in the absorption range of C=C and C=O (aldehydes and amides) bonds.

Option A: The compound must contain either a C=C bond or the C=O bond of an aldehyde or amide (peak at 1660 cm^{-1}), neither of which is present in the semi–structural formula given in option A. Therefore, option A is incorrect.

Option B: Since there is only one oxygen atom present in the compound, we must consider two cases. First, suppose the peak at 1660 cm^{-1} indicates the C=O bond of an aldehyde or amide and the peak at 3400 cm^{-1} indicates an N—H bond. In this case, option B would be wrong as there is no nitrogen atom present in the compound. The alternative case is that the peak at 3400 cm^{-1} indicates the O—H bond of an alcohol and the peak at 1660 cm^{-1} indicates the C=C bond of an alkene. Since the semi–structural formula given represents a saturated compound, this case is also not possible, so option B is incorrect.

Option C: From the semi–structural formula, the compound must contain at least one N—H bond, as well as a C=O bond, which is consistent with the IR spectrum shown. Therefore, option C is correct.

Option D: This semi–structural formula represents that of an alcohol. Therefore, for option D to be correct, the peak at 3400 cm^{-1} must indicate the O—H bond of an alcohol. Given the compound in option D only has one oxygen, the peak at 1660 cm^{-1} must indicate the C=C bond of an alkene, which is not possible as the semi–structural formula given represents a saturated compound. Therefore, option D is incorrect.

Adapted from VCAA 2020 exam Multiple choice Q21

STRATEGY

VCAA examinations often include questions in which students are given several different structures and asked to determine which structure is consistent with a given IR spectrum. In these cases, to be awarded full marks, you must both identify which bonds are present in the structure that is consistent with the IR spectrum, and identify which bonds are present in the structure that are not present on the spectrum. An example of this is shown in question 10.

PROGRESS QUESTIONS

Question 1

Which one of the following statements about IR spectroscopy is correct?

A. IR radiation is only absorbed at one wavelength.

B. An IR spectrum can be used to identify the mass of a sample.

C. In an IR spectrum, high transmittance corresponds to high absorption.

D. An IR spectrum can be used to determine the types of bonds present in an organic molecule.

Adapted from VCAA 2021 exam Multiple choice Q16

Question 2

In the IR spectrum of a carboxylic acid, there is most likely to be an absorption peak at

A. 1600 cm^{-1}

B. 1800 cm^{-1}

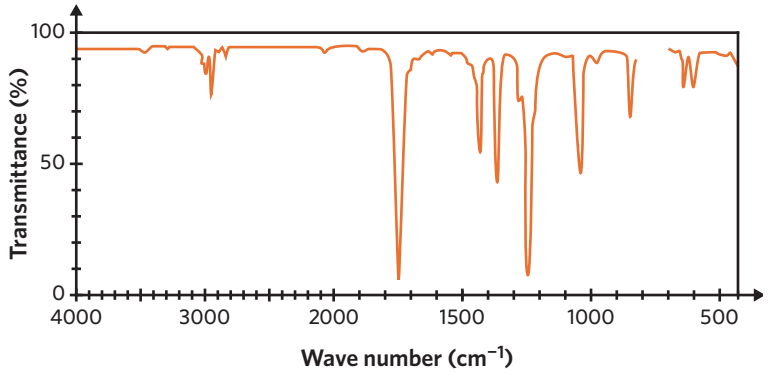
C. 3200 cm^{-1}

D. 3600 cm^{-1}

Continues →

Question 3

Consider the infrared spectrum shown.



Which of the following semi-structural formulas is consistent with the spectrum shown?

A. CH_2CHCH_3

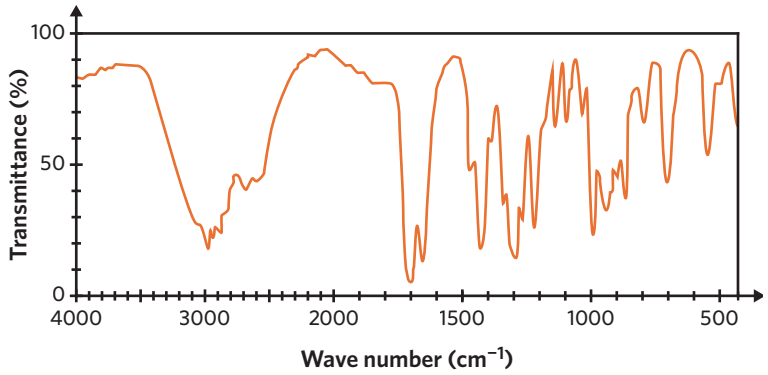
B. CH_3COCH_3

C. $CH_3CH(OH)CH_3$

D. CH_3COOCH_3

Question 4

Consider the infrared spectrum of an unknown compound shown.



Which of the following bonds are present in the unknown compound?

I. O–H

II. C–H

III. C=O

IV. C=C

V. N–H

A. III only

B. I & III only

C. I, II, III & IV only

D. I, II, IV & V only

Theory summary

- Certain wavelengths of infrared light increase the amount of bending and/or stretching of bonds between atoms.
- Each bond type absorbs energy from infrared light at a characteristic wavelength.
- Infrared spectroscopy is used to qualitatively determine the types of bonds present in an organic molecule.
- The types of bonds present in a molecule can be used to determine the functional groups present in the molecule.
- Each organic molecule has a unique fingerprint region (400 cm^{-1} to 1500 cm^{-1}).
- To identify which bond type is responsible for a peak in an infrared spectrum:
  1. Compare the wave numbe of the peak with the characteristic ranges for infrared absorption in the VCE Data Book.
  2. Consider the shape and strength of the peaks caused by different bond types.
  3. Distinguish between bond types that can appear in more than one type of compound, e.g. O—H (acid) or O—H (alcohol).

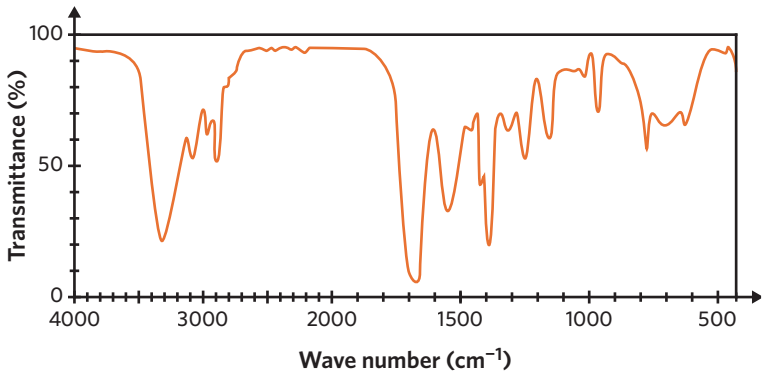
10B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 5–7.

The infra-red spectrum of an organic compound is shown.



Question 5 (1 MARK)

The absorbance peak at approximately 3300 cm^{-1} could be due to the presence of a

A. N—H bond. **B.** C—H bond. **C.** C=O bond. **D.** C=C bond.

Question 6 (1 MARK)

The absorbance peak at approximately 1680 cm^{-1} could be due to the presence of a

A. C—Cl bond. **B.** O—H bond. **C.** C—C bond. **D.** C=O bond.

Question 7 (1 MARK)

The organic compound that produces this spectrum is an

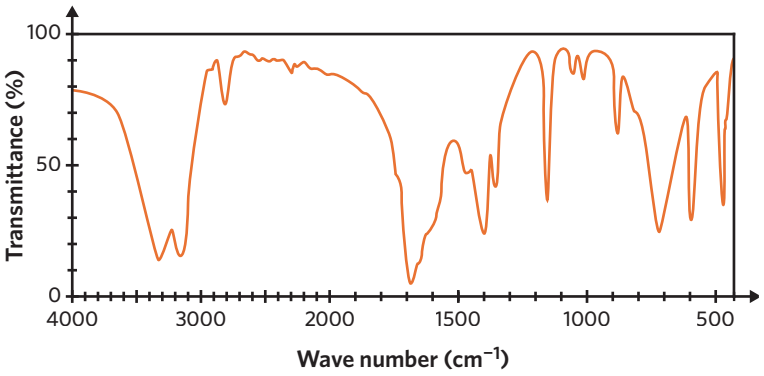
A. aldehyde. **B.** alcohol. **C.** amide. **D.** ester.

Adapted from VCAA 2017 exam Multiple choice Q17

Exam-style

Question 8 (1 MARK)

The infra-red spectrum of a pure organic compound is shown below.



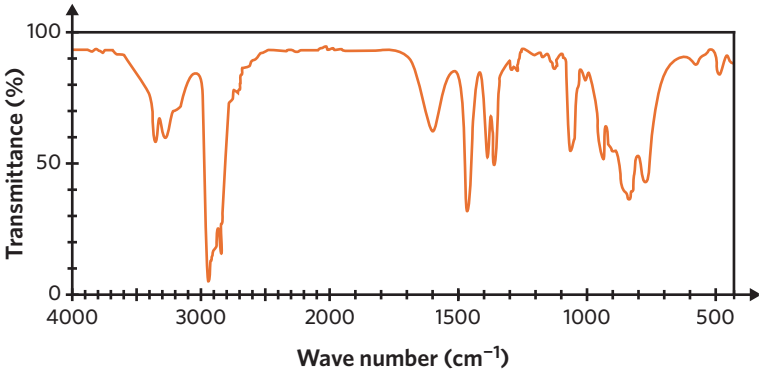
The organic compound is

A. CH_3CONH_2 **B.** CH_3COOCH_3 **C.** $(CH_3)_2CHNH_2$ **D.** $HOCH_2CH_2OH$

VCAA (NHT) 2022 exam Multiple choice Q13

Question 9 (4 MARKS)

A chemical that contains carbon, C, nitrogen, N, and hydrogen, H, in the ratio 4 : 1 : 11 is analysed using infra-red (IR) spectroscopy. The IR spectrum of the chemical is shown.



a. Identify the bonds responsible for the peaks at the following wave numbers.

i. 2956 cm^{-1} 1 MARK

ii. 3376 cm^{-1} 1 MARK

b. The chemical is found to have the molecular formula $C_4H_{11}N$. Draw a possible structural formula for this compound. 2 MARKS

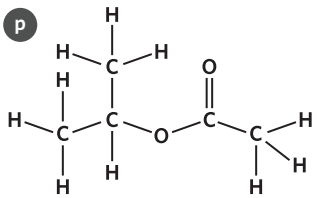
Adapted from VCAA 2018 exam Short answer Q3a, b

Key science skills

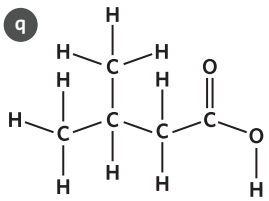
Question 10 (4 MARKS)

Two students are given a homework assignment that involves analysing an infrared spectrum (IR) and identifying an unknown compound. The unknown compound is one of the molecules shown.

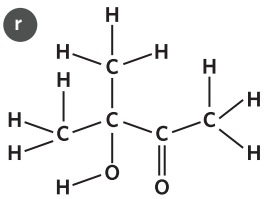
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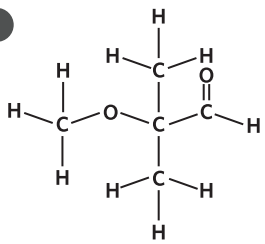
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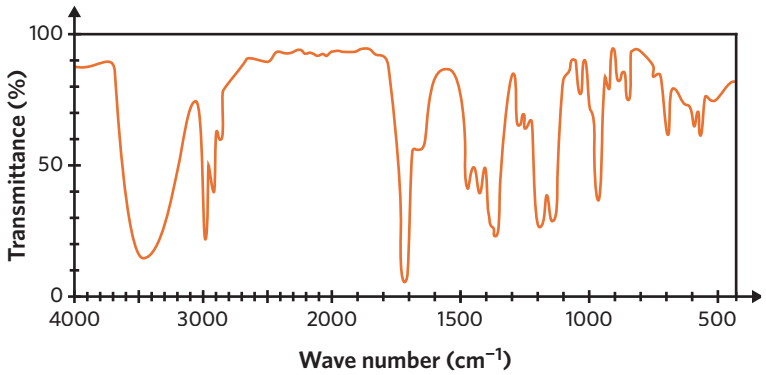
r



s



The IR spectrum of the unknown compound is shown.



Identify which of the four compounds is consistent with the IR spectrum. Justify your answer using data from the IR spectrum.

Adapted from VCAA 2021 exam Short answer Q7b

FROM LESSONS 12C & 12E

Questions from multiple lessons

Question 11 (6 MARKS)

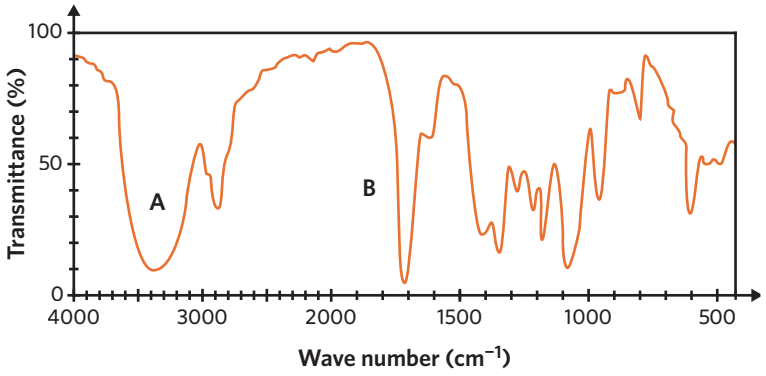
An unknown organic compound contains carbon, hydrogen, and oxygen. It is known that:

- The compound does not contain carbon-to-carbon double bonds (C=C).
- The molecular ion peak is found at a mass-to-charge ratio (m/z) of 74.
- The compound contains either three or four carbon atoms.

a. A small peak in the mass spectrum can be identified at $m/z = 75$. Explain the presence of this peak. 1 MARK

b. Use the information provided to give two possible molecular formulas for this compound. 2 MARKS

c. The infra-red (IR) spectrum of the compound is shown.



Identify the functional groups responsible for the absorption peaks labelled A and B in the IR spectrum. 2 MARKS

d. Draw the structural formula for the compound. 1 MARK

Adapted from VCAA 2019 exam Short answer Q8

FROM LESSONS 7A & 10A

Back to contents

10C Low resolution carbon-13 nuclear magnetic resonance spectroscopy

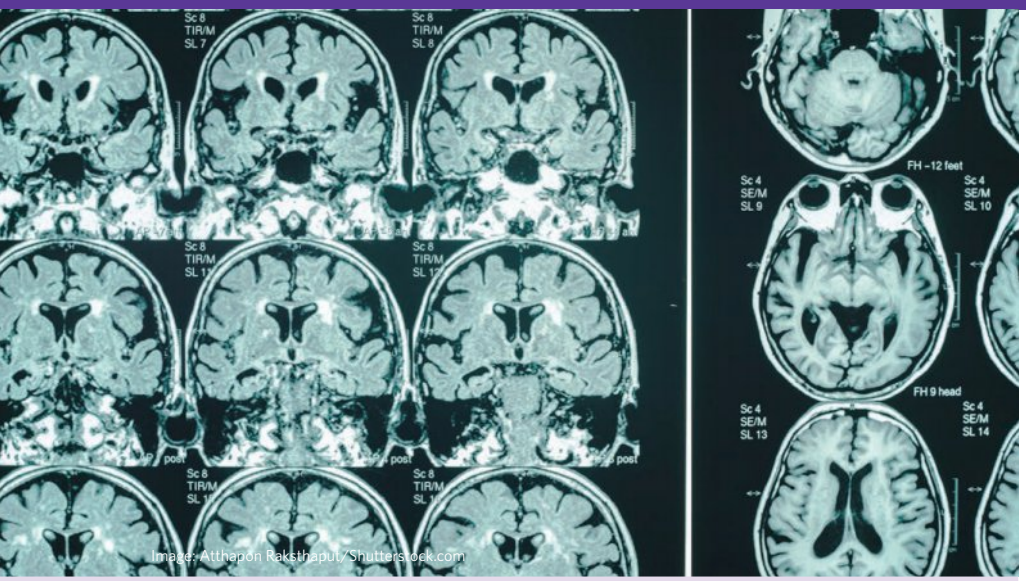


Image: Atthapon Raksthaput/Shutterstock.com

How is the magnetic resonance of atomic nuclei used to diagnose degenerative brain diseases?

Magnetic resonance imaging can be used to track decreases in the size of the brain that are characteristic of certain degenerative brain diseases. In this lesson, we will learn about how the magnetic resonance of **carbon-13 nuclei** can be used to determine the number of **non-equivalent carbon environments** in a compound.

KEY TERMS AND DEFINITIONS

^{13}C-NMR spectroscopy analytical technique that uses electromagnetic radiation and magnetic fields to provide information about the number of non-equivalent carbon environments in an organic compound

^{13}C-NMR spectrum spectrum of chemical shift values in ppm relative to a chemical standard (usually TMS)

Carbon-13 nucleus the nucleus of the carbon-13 isotope, which has an odd mass, allowing it to be detected by an NMR spectrometer

Chemical shift the resonant frequency of an atomic nucleus relative to a standard in a magnetic field

Equivalent carbon environments one or more carbon-13 nuclei attached to the same atom that are in identical chemical environments and are able to combine with adjacent carbon-13 nuclei to show as one peak in a spectrum

Non-equivalent carbon environments one or more carbon-13 nuclei attached to different atoms that are in different chemical environments

Symmetrical made up of exactly identical parts facing each other or around an axis

STUDY DESIGN DOT POINT

- structural determination of organic compounds by low resolution carbon-13 nuclear magnetic resonance (^{13}C-NMR) spectral analysis, using chemical shift values to deduce the number and nature of different carbon environments

10A 10B **10C** 10D 10E 10F

4.2.7.1 & 4.2.7.2 Low resolution ^{13}C-NMR & analysing low resolution ^{13}C-NMR spectra

ESSENTIAL PRIOR KNOWLEDGE

7A Functional groups

See question 81.

Low resolution ^{13}C-NMR & analysing low resolution ^{13}C-NMR spectra 4.2.7.1 & 4.2.7.2

The magnetic resonance of carbon-13 nuclei can be used to provide information about the number of carbon environments in an organic compound.

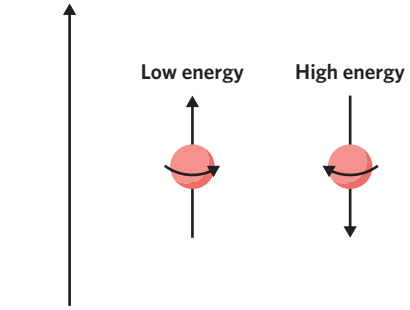


Figure 1 Directed orientation of nuclei with odd atomic mass in the presence of an external magnetic field

How do atomic nuclei behave as magnets?

In VCE chemistry Units 1 & 2, we learned that the nucleus of an atom is positively charged. In addition to being positively charged, atomic nuclei have angular momentum, which allows them to spin about their axes.

This combination of positive charge and nuclear spin enables atomic nuclei with odd atomic masses to act as tiny magnets. Two such atoms whose nuclei can behave as magnets are ^{13}C and ^{1}H. Because these nuclei can behave as magnets, when they are placed in a strong external magnetic field, they align themselves in certain directions as shown in figure 1.

MISCONCEPTION

'Any atoms can be analysed using nuclear magnetic resonance spectroscopy.'

When the nucleus contains an even number of protons and neutrons, their spins are paired so that they cancel each other out. However, in a nucleus with an odd number of protons and neutrons, the nucleus has a permanent overall spin which is the characteristic that allows them to be detected using NMR.

As shown in figure 1, when the magnetic poles of the nucleus align with the direction of the magnetic field, they exist in a lower energy state. Similarly, when the magnetic poles align against the direction of the magnetic field, they exist in a higher energy state. Hence, when a nucleus flips from a low to high energy state, energy has been absorbed, and when it flips from a high to low energy state, energy has been released. This energy is released in the form of electromagnetic radiation and is known as a **chemical shift** measured in parts per million (ppm).[1]

KEEN TO INVESTIGATE?

[1] **How does the magnetic behaviour of certain atoms allow scientists to photograph the brain?**
Search YouTube: How does an MRI machine work?

KEEN TO INVESTIGATE?

[2] **Why is TMS used as a reference compound in NMR spectroscopy?**
Search YouTube: Why TMS is used as reference sample in NMR Spectroscopy | #tetramethylsilane

USEFUL TIP

In VCE chemistry, only low resolution ^{13}C-NMR spectroscopy is examined. We will explore high and low resolution ^{1}H-NMR spectroscopy in lesson 10D.

MISCONCEPTION

'The number of peaks on the ^{13}C-NMR spectrum is equal to the number of carbon-13 nuclei in an organic compound.'

Certain carbon environments are equivalent to each other, and are hence combined, showing as only 1 peak on the spectrum with greater intensity.

How is low resolution ^{13}C–NMR used to determine the number of non-equivalent carbon environments in an organic compound?

In low resolution **carbon–13 nuclear magnetic resonance (^{13}C-NMR) spectroscopy**, the chemical shift of ^{13}C atoms in certain carbon groups is measured relative to a reference compound, which is assigned a chemical shift of 0 ppm. All of the ^{13}C-NMR spectra encountered in VCE chemistry will use TMS (tetramethylsilane, $(CH_3)_4Si$) as the reference compound.[2] The output of ^{13}C-NMR spectroscopy is a **^{13}C-NMR spectrum**, such as the one shown in figure 2, that can be used to determine the number and possible types of non-equivalent (unique) carbon environments in an organic compound.

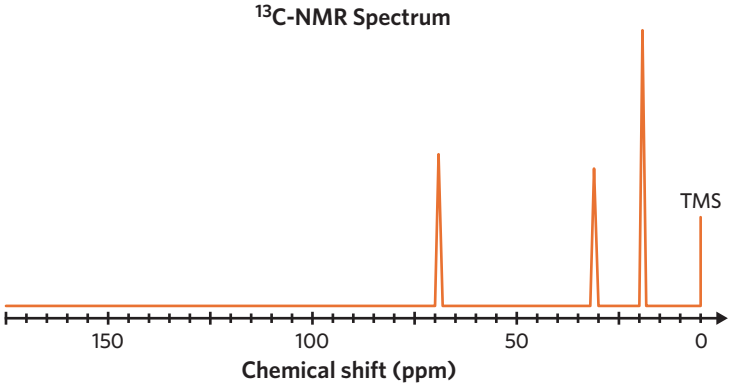
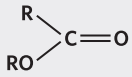
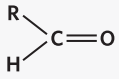


Figure 2 ^{13}C-NMR spectrum

The number of non-equivalent carbon environments is simply equal to the number of peaks (aside from the TMS peak) shown on the spectrum. So, for the spectrum given in figure 2, the compound has 3 non-equivalent carbon environments as there are 3 peaks shown. To determine the type of carbon environment, all we need to do is compare the chemical shift values of the peaks shown on the spectrum to the typical ^{13}C shift values relative to TMS = 0 given in the VCE Data Book (table 1).

Table 1 Typical ^{13}C shift values relative to TMS = 0

Type of carbon	Chemical shift (ppm)
R—CH_3	8–25
R—CH_2—R	20–45
R_3—CH	40–60
R_4—C	36–45
R—CH_2—X	15–80
R_3C—NH_2, R_3C—NR	35–70
R—CH_2—OH	50–90
RC≡CR	75–95
R_2C=CR_2	110–150
RCOOH	160–185
	165–175
	190–200
R_2C=O	205–220

Using the values given in table 1, we can deduce the types of carbon environments that could be responsible for each peak (figure 3).

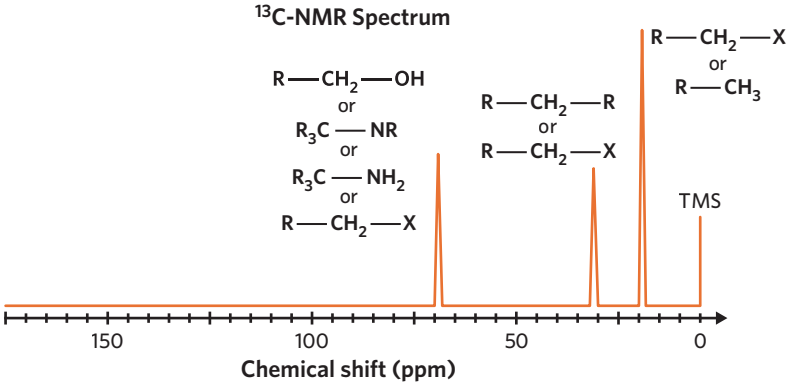


Figure 3 The possible carbon environments responsible for each peak in the ^{13}C-NMR spectrum

Figure 3 shows the key limitation of using ^{13}C-NMR alone; it is not possible to identify the exact types of carbon environments present in the compound. For example, the peak with a chemical shift value of approximately 68 ppm could be caused by a carbon environment containing any one of a hydroxyl, carbonyl, amino, or halogen (shown as X in the VCE Data Book) functional group. However, when provided with additional information such as the types of atoms present in a compound or the functional groups present in an organic compound, ^{13}C-NMR can allow us to determine the structure of an organic compound. The skill of combining analytical techniques will be explored in lesson 10F.

How can equivalent carbon environments affect the number of peaks on a ^{13}C-NMR spectrum?

As mentioned earlier, the number of peaks on a ^{13}C-NMR spectrum indicates the number of non-equivalent carbon environments in a compound. The term non-equivalent is used as in some cases, there are **equivalent carbon environments** that combine, showing as one peak with greater intensity.

To determine which carbon environments are equivalent in a compound, we simply need to look at the sequence of bonds attached to each carbon. If two or more carbon-13 nuclei have the same bond sequence, they will have the same carbon environment and show as only one peak on a ^{13}C-NMR spectrum. For example, consider the structure of 2-methylpentane shown in figure 4.

USEFUL TIP

Whilst it is difficult to understand how two carbon environments can be combined into one, it is important to remember that the structural formulas of compounds are simply models, and do not show the ability of single bonds to rotate. The rotational ability of single bonds in **symmetrical** compounds gives equivalent carbon environments the same chemical shift value, causing them to show as one peak on a ^{13}C-NMR spectrum.

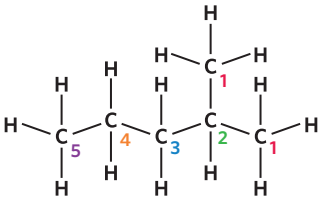
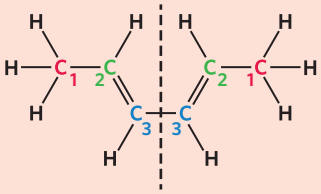


Figure 4 Structural formula of 2-methylpentane

The carbon-13 nuclei labelled '1' in figure 4 have the same sequence of bonds, and are therefore equivalent carbon environments. So, despite having 6 carbon-13 nuclei, 2-methylpentane has only 5 non-equivalent carbon environments. Hence, the ^{13}C-NMR spectrum of 2-methylpentane contains only 5 peaks, as shown in figure 5.

STRATEGY

To determine the number of non-equivalent carbon environments in an organic compound, we can use the symmetry of organic compounds. By first drawing the structural formula, we can then draw lines of symmetry to determine which carbon environments are equivalent.



Any organic compound with at least one line of symmetry will have at least two equivalent carbon environments.

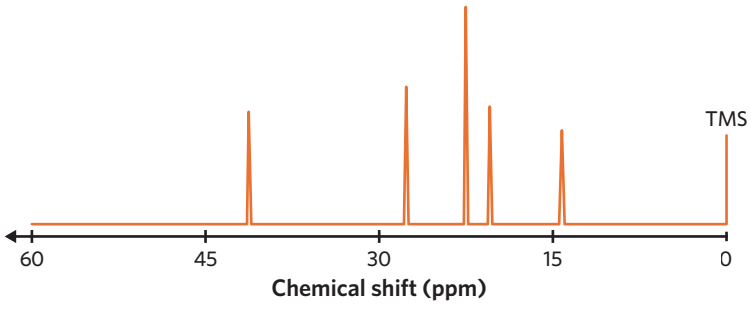
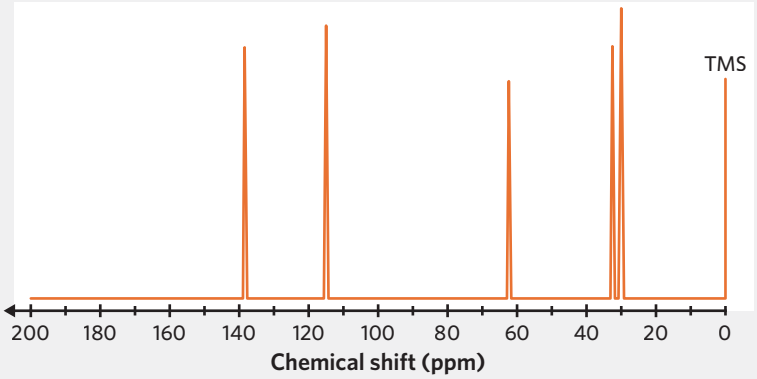


Figure 5 ^{13}C-NMR spectrum of 2-methylpentane

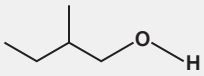
Given that peaks caused by the combining of equivalent carbon environments appear with greater intensity, the peak at a chemical shift of approximately 23 ppm must have been caused by the carbon environments labelled '1' in figure 4.

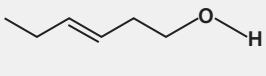
WORKED EXAMPLE 1

The ^{13}C-NMR spectrum of an organic compound is shown.

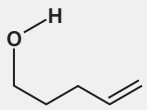


The organic compound could be

A. 

B. 

C. 

D. 

What information is presented in the question?

The ^{13}C-NMR spectrum of an organic compound.

What is the question asking us to do?

Determine which of the organic compound structures is consistent with the ^{13}C-NMR spectrum.

What strategies do we need in order to answer the question?

1. Determine the number of peaks shown on the spectrum.
2. Identify types of carbon atoms that could be responsible for each peak using the chemical shift values in the VCE Data Book.
3. Determine the number of non-equivalent carbon environments in each compound given.
4. Compare the types of carbon environments present in each compound given, to those indicated by the spectrum.

Answer

There are 5 distinct peaks shown on the ^{13}C-NMR spectrum, so there are 5 non-equivalent carbon environments in the compound. The peaks at chemical shifts of 29 and 32 ppm could be caused by either R−CH_2−R or R−CH_2−X. The peak at a chemical shift of 62 ppm could be caused by any of R−CH_2−X, R_3C-NH_2, R_3C-NR, or R−CH_2−OH. The peaks at chemical shifts of 115 and 139 ppm can only be caused by $R_2C=CR_2$. Hence, the compound must have 5 non-equivalent carbon environments and it must contain a C=C double bond.

Option A: The structure contains 5 non-equivalent carbon environments, however it does not have a C=C double bond. Therefore, option A is incorrect.

Option B: The structure contains 6 non-equivalent carbon environments. Therefore, option B is incorrect.

Option C: The structure contains 5 non-equivalent carbon environments, however it does not have a C=C double bond. Therefore, option C is incorrect.

Option D: The structure contains 5 non-equivalent carbon environments and a C=C double bond. Therefore, option D is correct.

Adapted from VCAA 2022 exam Multiple choice Q28

PROGRESS QUESTIONS

Question 1

The ^{13}C-NMR spectrum of an unknown organic compound has three distinct peaks. How many carbon-13 nuclei does the compound have?

A. 2

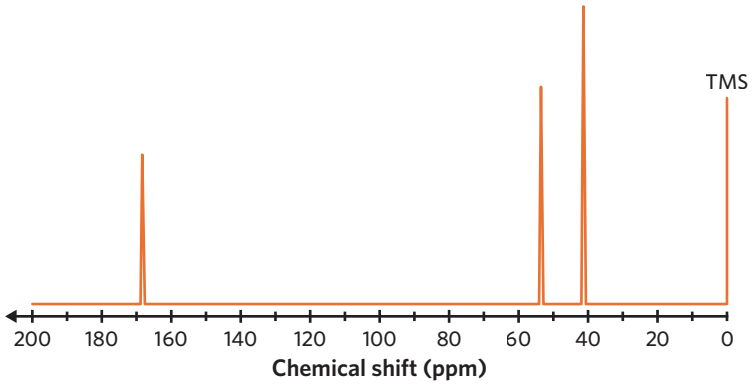
B. 3

C. 4

D. Cannot be determined from the information given

Question 2

Consider the ^{13}C-NMR spectrum shown.



What are the two possible carbon environments that can produce the peak at 168 ppm?

A. RCOOH (carboxylic acid) and RCOOR (ester)

B. RCOOH (carboxylic acid) and $R_2C{=}CR_2$ (alkene)

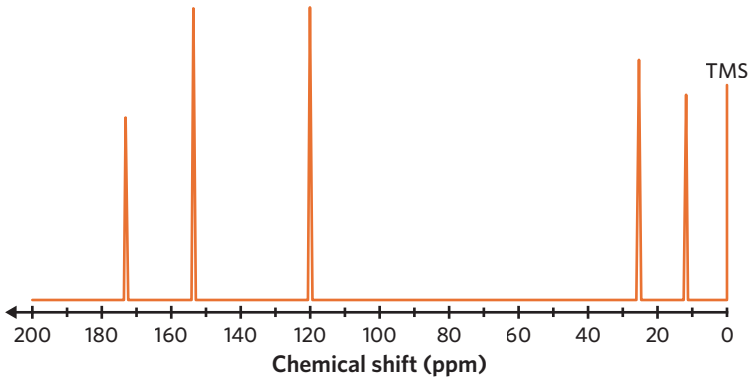
C. RCOOR (ester) and RCHO (aldehyde)

D. RCOOR (ester) and $R_2C{=}O$ (ketone)

Adapted from 2022 VCAA exam Short answer Q5a

Question 3

An unknown compound was analysed using low resolution ^{13}C-NMR spectroscopy.



The unknown compound contains

A. 5 equivalent carbon environments.

B. 5 non-equivalent carbon environments.

C. 6 equivalent carbon environments.

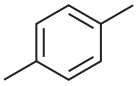
D. 6 non-equivalent carbon environments.

Adapted from VCAA (NHT) 2018 exam Short answer Q2bi

Continues →

Question 4

Consider the compound shown.



How many peaks would be expected to appear in the ^{13}C-NMR spectrum of this compound?

A. 3 **B.** 4 **C.** 6 **D.** 8

Theory summary

- A chemical shift occurs when the nucleus of an atom flips from a high to low energy state.
- The chemical shift values on a ^{13}C-NMR spectrum are measured relative to TMS, which is assigned a chemical shift value of 0 ppm.
- The chemical shift value of a peak can be compared to the values given in the VCE Data Book to determine the type of carbon environment responsible for the peak.
- A peak on a ^{13}C-NMR spectrum represents a non-equivalent carbon environment.
- Equivalent carbon environments combine, showing as one peak with a higher intensity on a ^{13}C-NMR spectrum.
- Carbon environments are equivalent when they are attached to the same sequence of bonds and atoms.
- Symmetrical compounds will always have at least two equivalent carbon environments.
- Asymmetrical compounds will never have equivalent carbon environments; i.e. the number of carbon-13 nuclei is equal to the number of peaks in the ^{13}C-NMR spectrum.

10C Questions

Deconstructed

Use the following information to answer questions 5–7.

An organic compound has a molar mass of 88 g mol^{-1}. The ^{13}C-NMR spectrum of the organic compound shows four distinct peaks. The organic compound is known to be one of the following.

I. Butan-1-ol

II. 2-methylbutan-1-ol

III. 2-methylbutan-2-ol

IV. Dimethylpropanol

Question 5 (1 MARK)

Which of the following correctly identifies the compound(s) with a molar mass of 88 g mol^{-1}?

A. I only

B. II and III only

C. II, III, and IV only

D. I, II, and IV only

Question 6 (1 MARK)

Which of the following correctly identifies the compound(s) with four non-equivalent carbon environments?

A. I only

B. I and III only

C. II and IV only

D. III and IV only

Question 7 (3 MARKS)

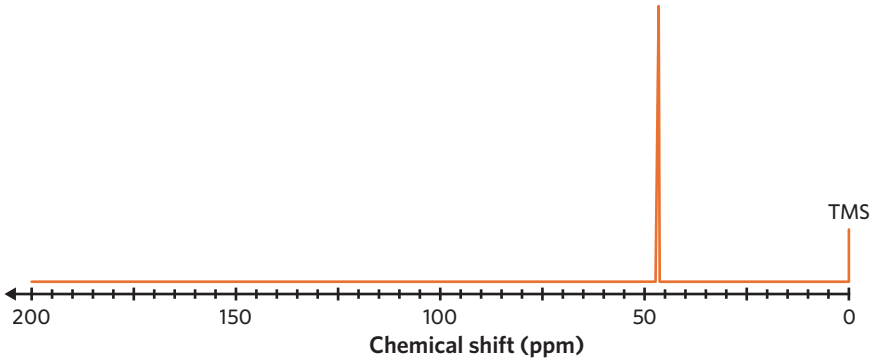
Which of the four compounds is most likely to be the compound represented in the ^{13}C-NMR spectrum? Explain.

Adapted from 2019 VCAA exam Multiple choice Q27

Exam-style

Question 8 (3 MARKS)

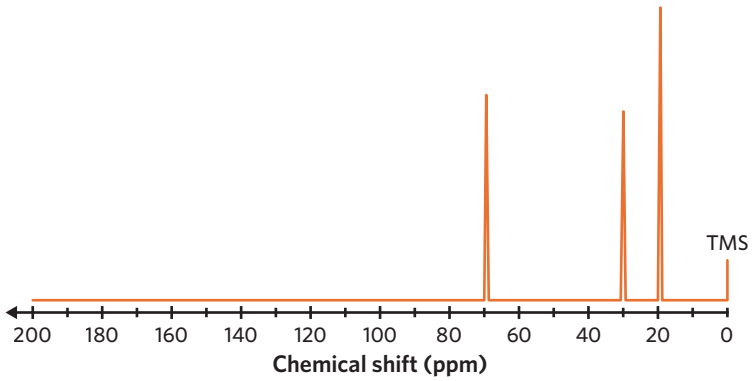
A sample of diaminomethane is analysed using ^{13}C-NMR spectroscopy. A spectrum obtained is shown.



Is this spectrum consistent with the structure of diaminomethane? Justify your answer.

Question 9 (1 MARK)

Consider the ^{13}C-NMR spectrum shown.



The ^{13}C-NMR spectrum shown corresponds to which one of the following compounds?

A. Propane

B. Methylbutane

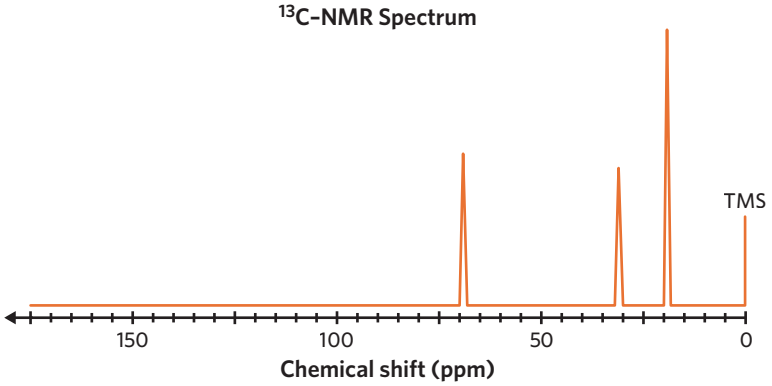
C. Methylpropan-1-ol

D. Methylpropan-2-ol

VCAA 2014 exam Multiple choice Q15

Question 10 (4 MARKS)

The ^{13}C-NMR spectrum for an unidentified molecule is given.



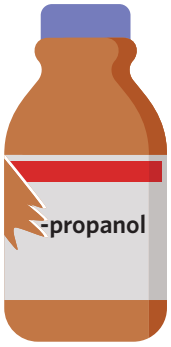
a. What is the purpose of the peak labelled TMS in the process of ^{13}C-NMR spectroscopy? 1 MARK

b. A student states that the unidentified molecule is methylpropan-2-ol. Explain whether this response is consistent with the ^{13}C-NMR spectrum given. 3 MARKS

Key science skills

Question 11 (4 MARKS)

While cleaning out his lab, Mohammad notices that the label on a bottle of propanol has been partially scratched off.



a. Give the semi-structural formulas for the two isomers of propanol. 1 MARK

b. Write a method that Mohammad can use to determine which isomer of propanol the bottle contains, using ^{13}C-NMR spectroscopy. 3 MARKS

FROM LESSONS 12A & 12E

Questions from multiple lessons

Question 12 (8 MARKS)

A mixture contains several different organic liquids, all of which boil at temperatures greater than 50°C. The compounds present in the mixture are separated. One of the compounds, compound Y, is an alcohol with the molecular formula $C_4H_{10}O$.

a. Draw the structural formulas, showing all bonds, of the four possible alcohols with the molecular formula of $C_4H_{10}O$. 4 MARKS

b. Compound Y contains 3 distinct peaks in its ^{13}C-NMR spectrum and undergoes a reaction with acidified $Cr_2O_7^{2-}$(aq) to produce a carboxylic acid. What evidence about the structure of Y can be gained from this information? 2 MARKS

c. Based on the above evidence, identify compound Y by first circling the structural formula in part **a** that corresponds to compound Y and then writing the systematic name of compound Y. 2 MARKS

Adapted from VCAA 2008 Exam 1 Short answer Q4

FROM LESSONS 7A, 7B & 8A

Back to contents

10D Low & high resolution proton nuclear magnetic resonance spectroscopy

STUDY DESIGN DOT POINT

- structural determination of organic compounds by low and high resolution proton nuclear magnetic resonance (^{1}H-NMR) spectral analysis, using chemical shift values, integration curves (where the height is proportional to the area underneath a peak) and peak splitting patterns (excluding coupling constants), and application of the n + 1 rule (where n is the number of neighbouring protons) to deduce the number and nature of different proton environments

10A 10B 10C **10D** 10E 10F

4.2.8.1 & 4.2.8.2 Low and high resolution ^{1}H-NMR & analysing low and high resolution ^{1}H-NMR spectra

ESSENTIAL PRIOR KNOWLEDGE

7A Functional groups
7B IUPAC naming
10C Chemical shift

See questions 82–84.



Image: Marko Aliaksandr/Shutterstock.com

How is proton nuclear magnetic resonance spectroscopy used in MRI machines to diagnose multiple sclerosis?

Proton nuclear magnetic resonance (NMR) spectroscopy, or **^{1}H-NMR (proton NMR) spectroscopy**, is used in MRI machines to identify tissue damage in the brain that is characteristic of multiple sclerosis. In this lesson, we will learn about how the magnetic resonance of protons (**hydrogen nuclei**) can be used to determine the number of **non-equivalent proton environments** in a compound, as well as the number, nature and ratio of the protons in a compound.

KEY TERMS AND DEFINITIONS

^{1}H-NMR (proton NMR) spectroscopy analytical technique that uses electromagnetic radiation and magnetic fields to provide information about the number of non-equivalent proton environments in an organic compound and the number of protons in those environments

^{1}H-NMR spectrum spectrum of chemical shift values in ppm relative to a chemical standard (usually TMS)

Equivalent proton environments one or more protons (hydrogen nuclei) attached to the same atom that are in identical environments and are able to combine with adjacent protons to show as one set of peaks in a spectrum

High resolution showing both singular peaks and distinct sets of peaks with splitting patterns

Hydrogen nucleus the nucleus of the hydrogen atom, which has an odd mass, allowing it to be detected by an NMR spectrometer

Integration curve curve on a ^{1}H-NMR spectrum showing the relative number of protons in a proton environment

Low resolution showing only singular peaks without splitting patterns

n + 1 rule the number of splits in a peak is equal to the number of protons in the neighbouring proton environment(s) (n) + 1

Non-equivalent proton environments one or more protons (hydrogen nuclei) attached to different atoms that are in different chemical environments, causing splitting to adjacent protons

Splitting pattern the number of peaks shown in a set of peaks corresponding to a single non-equivalent proton environment

Low and high resolution ^{1}H-NMR & analysing low and high resolution ^{1}H-NMR spectra 4.2.8.1 & 4.2.8.2

Low and **high resolution** ^{1}H-NMR spectroscopy are analytical techniques used in conjunction with other analytical techniques to gain information about the structure of organic compounds.

How can low resolution ^{1}H-NMR be used in determining the structure of organic compounds?

In lesson 10C, we learned that the nuclei of atoms with odd atomic masses have an overall spin that allows them to behave as tiny magnets. So far, we have looked at how this property is used in carbon-13 nuclear magnetic resonance (NMR) spectroscopy to provide information about the number of non-equivalent carbon environments in a compound. There are two other key types of NMR spectroscopy covered in VCE chemistry: low resolution and high resolution ^{1}H-NMR spectroscopy, also known as proton NMR spectroscopy.

Low resolution ^{1}H-NMR spectroscopy is used to obtain the following information about an organic compound:

- the number of non-equivalent proton environments
- the ratio of the number of protons in each of these environments
- the possible types of proton environments present.

The output of low resolution ^{1}H-NMR spectroscopy is a **^{1}H-NMR spectrum** such as the one shown in figure 1.

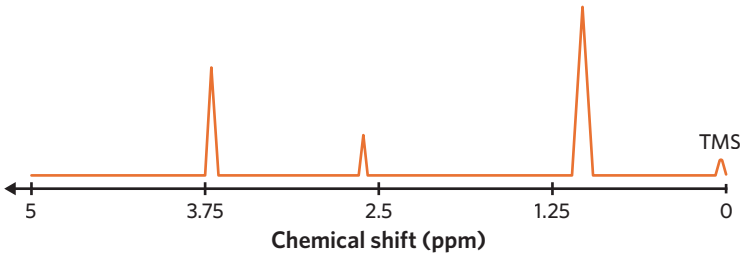


Figure 1 A low resolution proton NMR spectrum

USEFUL TIP

Since hydrogen atoms contain only one proton and one electron, when they ionise to form hydrogen ions, they can simply be referred to as a proton.

USEFUL TIP

The spectra in lessons 10B (IR spectroscopy), 10C (^{13}C-NMR), and 10D (high and low resolution ^{1}H-NMR) have atypical horizontal axes: instead of increasing from left to right, the values increase from right to left.

In figure 1, there are three distinct peaks. Like in ^{13}C-NMR, each of these peaks represents a non-equivalent proton environment. Unlike in ^{13}C-NMR, however, each of the peaks is curved. Because they are curved, there is an area under each peak. **Integration curves** are used to determine the ratio of the areas under each peak, which indicate the ratio of the number of protons in each non-equivalent proton environment (figure 2).

USEFUL TIP

As a ruler is necessary to measure integration curves on low resolution ^{1}H-NMR spectra, it is important to bring a ruler into every SAC and examination in VCE chemistry.

MISCONCEPTION

'The height of each peak is used to determine the number of hydrogen atoms in each environment.'

It is the relative heights of the integration curves, where the height is proportional to the area underneath each peak, that is used to determine the ratio of protons that share **equivalent proton environments**.

USEFUL TIP

The height of an integration curve on a proton NMR spectrum can also be referred to as the integration value.

USEFUL TIP

In some cases, the areas underneath the peaks on a low resolution ^{1}H-NMR spectrum may be given instead of integration curves. In such cases, the ratios of the areas underneath the peaks can be used to determine the number of protons in each proton environment.

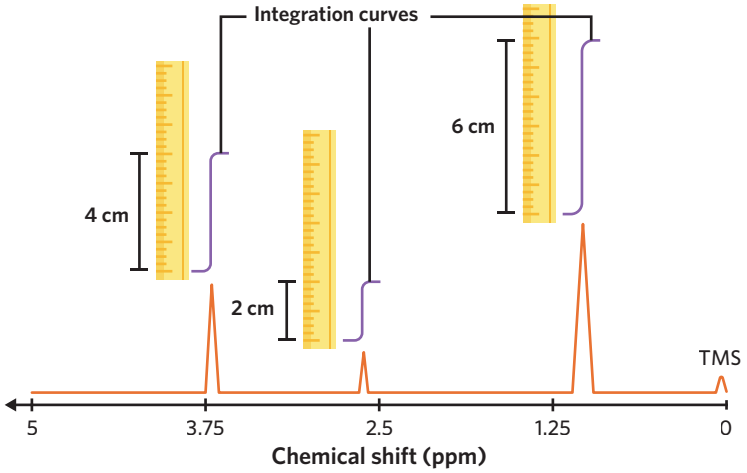


Figure 2 Integration curves on a low resolution ^{1}H-NMR spectrum showing a 2 : 1 : 3 ratio of protons

To determine the ratios of the areas, a ruler should be used to measure the height of each integration curve. In the case of figure 2, there is a 4 cm : 2 cm : 6 cm ratio moving from left to right. We can simplify this ratio to 2 : 1 : 3, indicating that there are 2 protons in the leftmost peak (approx. 3.65 ppm), 1 proton in the middle peak (approx 2.6 ppm), and 3 protons in the rightmost peak (approx. 1.0 ppm).

The VCE Data Book lists the chemical shift values relative to TMS = 0 of different types of protons, some of which are given in table 1.

Table 1 Typical proton shift values relative to TMS = 0 (complete list provided in VCE Data Book)

Type of proton	Chemical shift (ppm)
R—CH_3	0.9–1.0
CH_3—C(=O)—OR or CH_3—C(=O)—NHR	2.0
R—C(=O)—CH_3	2.1–2.7
R—CH_2—X (X = F, Cl, Br or I)	3.0–4.5
R—CH_2—OH or R_2—CH—OH	3.3–4.5
R—O—CH_3 or R—O—CH_2R	3.3–3.7
R—O—H	1–6 (varies considerably under different conditions)
R—NH_2	1–5
R—C(=O)—H	9.4–10.0
R—C(=O)—O—H	9.0–13.0

We can use these chemical shift values in table 1 to deduce the possible types of proton environments responsible for each peak in a ^{1}H-NMR spectrum (figure 3) (same spectrum as figures 1 and 2).

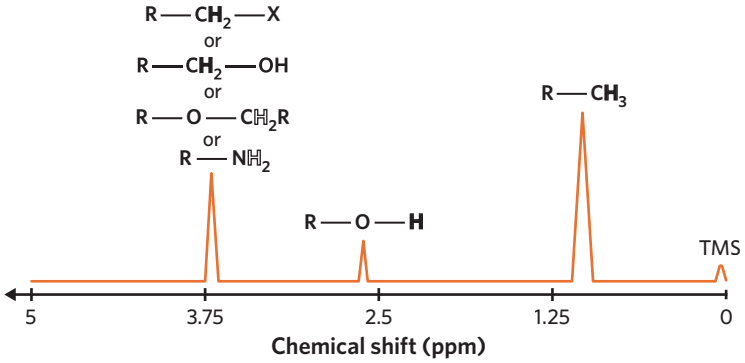


Figure 3 The possible proton environments responsible for each peak in the ^{1}H-NMR spectrum

As shown in figure 3, the peak at a chemical shift of approximately 3.65 ppm could be caused by a proton environment containing either a C**H**$_2$ bonded to a halogen, hydroxyl, or ether group, or the N**H**$_2$ of an amine. It is important to note that whilst the chemical shift ranges of a C**H**$_3$ bonded to an ether group or the O—**H** group of a primary alcohol are consistent with the chemical shift value of the leftmost peak, they are not possible types of proton environments as this particular environment must contain exactly 2 protons.

USEFUL TIP

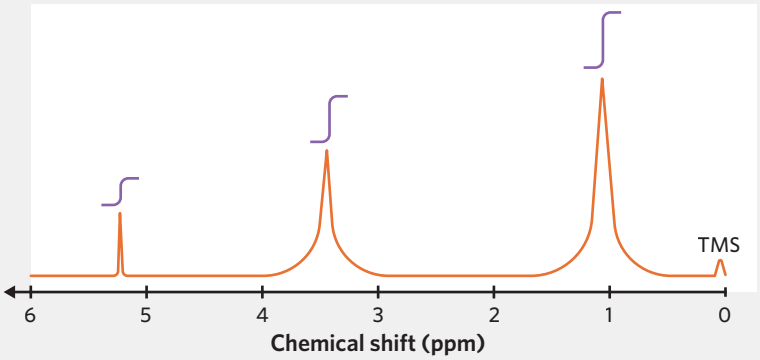
The –X in a R–C**H**$_2$–X group is used to represent a halogen group. The halogens (halogens) include fluorine, chlorine, bromine, and iodine.

USEFUL TIP

In spectrums produced from low resolution ^{1}H-NMR spectroscopy, the peaks are not split – they show as single peaks.

WORKED EXAMPLE 1

The low resolution ^{1}H-NMR spectrum of an unknown organic compound is shown.



The ratio of the protons in the unknown organic compound is equal to

	5.3 ppm	3.4 ppm	1.0 ppm
A.	2	3	3
B.	0.5	1	2
C.	0.5	1.5	1.5
D.	0.5	1	1.5

What information is presented in the question?

The low resolution ^{1}H-NMR spectrum of an unknown organic compound.

What is the question asking us to do?

Identify which of the ratios of protons given is consistent with the low resolution ^{1}H-NMR spectrum given.

What strategies do we need in order to answer the question?

1. Identify the ratio of protons in each non-equivalent proton environment.
2. Compare the ratios of protons given in each answer to the ratio of the heights of the integration curves.

Answer

Using a ruler to measure the height of the integration curves, the ratio of protons in each non-equivalent proton environment is 1 : 2 : 3. The only ratio given that is equivalent to this ratio is 0.5 : 1 : 1.5 given in option D. Therefore, option D is correct.

Why is high resolution ^{1}H-NMR used in determining the structure of organic compounds?

As in low resolution ^{1}H-NMR, high resolution ^{1}H-NMR spectroscopy can be used to obtain the following information about an organic compound:

- the number of non-equivalent proton environments
  - equal to the number of distinct peaks on a ^{1}H-NMR spectrum
- the possible types of proton environments present.
  - indicated by the chemical shifts of each peak (see VCE Data Book).

However, high resolution ^{1}H-NMR spectroscopy is typically favoured over low resolution ^{1}H-NMR spectroscopy in industry. This is due to the **splitting patterns** shown in a high resolution proton NMR spectrum (figure 4). The splitting patterns provide a useful piece of information that is absent from a low resolution spectrum: the number of protons in neighbouring proton environments. Due to this limitation of low resolution ^{1}H-NMR spectra, high resolution proton NMR spectroscopy is often favoured over the low resolution alternative.[1]

KEEN TO INVESTIGATE?

[1] **How is proton NMR spectroscopy applied in the real world?**
Search: 7 uses of NMR spectroscopy

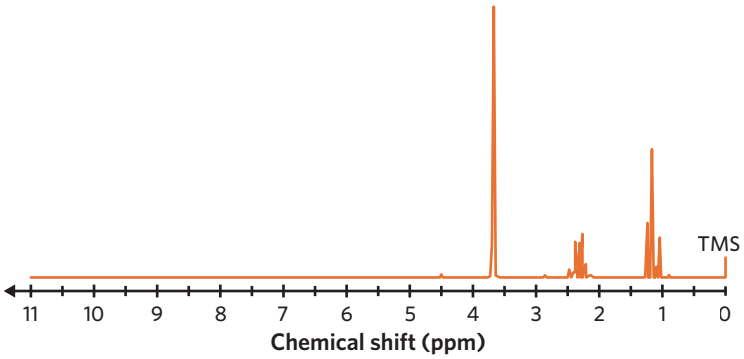


Figure 4 A high resolution proton NMR spectrum

The term splitting pattern refers to the number of splits shown in each distinct peak on a high resolution spectrum. The different types of splitting patterns that may be examined in VCE chemistry are shown in figure 5.



Figure 5 Splitting patterns in high resolution proton NMR spectra

The number of splits in a peak is equal to the number of protons in the neighbouring proton environment(s) (n) + 1. This is known as the **n + 1 rule**, where n = number of neighbouring protons. For example, a proton environment with 3 protons in the neighbouring proton environment(s) will appear as a quartet on a proton NMR spectrum.

How can equivalent proton environments affect the splitting patterns and number of peaks on a ^{1}H-NMR spectrum?

In lesson 10C, we learned how to differentiate between equivalent and non-equivalent carbon environments. Very similar principles can be used to identify equivalent proton environments in organic compounds. To determine which proton environments are equivalent in a compound, we simply need to look at the sequence of bonds attached to each proton. If two or more protons have the same bond sequence, they are said to be in chemically equivalent proton environments.

As a result, they combine, showing as only one peak on a low resolution ^{1}H-NMR spectrum, or as a set of peaks on a high resolution ^{1}H-NMR spectrum. For example, consider the structure of methyl propanoate shown in figure 6.

Figure 6 shows that the protons labelled '1' are chemically equivalent proton environments, meaning they show as only one peak on ^{1}H-NMR spectrum. Additionally, since there are 2 protons in the neighbouring proton environment, we can use the n + 1 rule to determine that the protons in environment '1' will show as a triplet, a peak with a splitting pattern of 3. Similarly, the protons labelled '2' are chemically equivalent proton environments, and appear as a quartet due to their 3 neighbouring protons. The protons labelled '3' are also chemically equivalent, but have no neighbouring protons and hence show as a single peak or singlet on a ^{1}H-NMR spectrum.

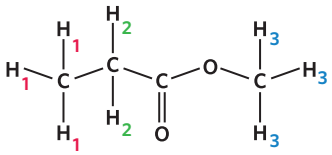


Figure 6 Structural formula of methyl propanoate

When two environments are chemically equivalent, they combine and show as one peak or set of peaks on an IR spectrum. Another example of the combining of chemically equivalent proton environments is shown in the structure of 2-propanol (figure 7).

In figure 7, the protons labelled '1' are all chemically equivalent, and have only one proton (labelled '2') in the neighbouring proton environment. Hence, according to the n + 1 rule, the peak corresponding to these protons on a high resolution ^{1}H-NMR spectrum would appear as a doublet. The proton labelled '2' has no chemically equivalent protons and six neighbouring protons (labelled '1'), so its peak would appear as a septet. The proton labelled '3' has no chemically equivalent protons and no neighbouring protons, so its peak would appear as a singlet.

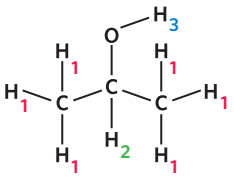
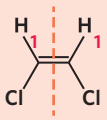


Figure 7 Structural formula of 2-propanol

STRATEGY

To determine the number of non-equivalent proton environments in an organic compound, we can use the symmetry of organic compounds. By first drawing the structural formula, we can then draw lines of symmetry to determine which proton environments are equivalent.



Any organic compound with at least one line of symmetry (and at least one hydrogen atom on either side of a line of symmetry) will have at least two equivalent proton environments.

MISCONCEPTION

'The number of peaks on the ^{1}H-NMR spectrum is equal to the number of protons in an organic compound.'

Certain proton environments are equivalent to each other, and hence combine, showing as only 1 peak (low resolution) or one set of peaks (high resolution) on the ^{1}H-NMR spectrum.

WORKED EXAMPLE 2

The ^{1}H-NMR spectrum of an organic compound has three unique sets of peaks: a single peak, seven peaks (septet), and two peaks (doublet). The compound is

A. 3-methylbutanoic acid.

B. 2-methylpropanoic acid.

C. 2-chloro-2-methylpropane.

D. 1,2-dichloro-2-methylpropane.

What information is presented in the question?

The ^{1}H-NMR spectrum of the compound has a singlet, a septet, and a doublet.

Continues →

What is the question asking us to do?

Determine which of the compounds is consistent with the splitting patterns of each peak.

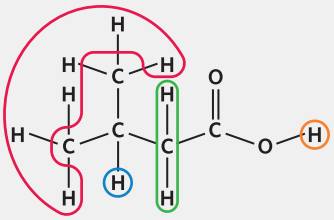
What strategies do we need in order to answer the question?

1. Determine the number of non-equivalent proton environments in the compound represented by the spectrum.
2. Compare the number of non-equivalent proton environments in the compounds given in each answer.
3. Compare the expected splitting patterns of each set of peaks in the compounds given using the n + 1 rule.

Answer

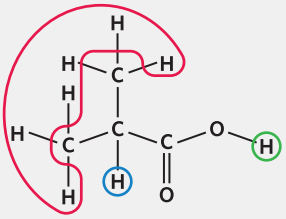
Since there are three unique sets of peaks, there must be three non-equivalent proton environments in the compound. To determine the number of non-equivalent proton environments and expected splitting patterns for each of the compounds given, we can draw the structural formulas of each compound.

Option A:



3-methylbutanoic acid has 4 non-equivalent proton environments, so option A is incorrect.

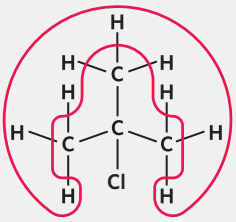
Option B:



2-methylpropanoic acid has 3 non-equivalent proton environments, which is consistent with the information given. The expected splitting patterns for the three peaks on the ^{1}H-NMR spectrum of 2-methylpropanoic acid are a septet (6 neighbouring protons), a doublet (1 neighbouring proton), and a singlet (no neighbouring protons), which is also consistent with the information given.

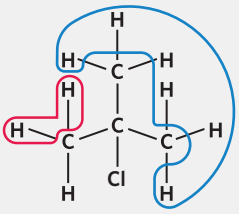
Hence, option B is correct.

Option C:



2-chloro-2-methylpropane has 1 type of proton environment, so option C is incorrect.

Option D:



1,2-dichloro-2-methylpropane has 2 non-equivalent proton environments, so option D is incorrect.

Adapted from VCAA 2021 exam Multiple choice Q30

PROGRESS QUESTIONS

Question 1

In ^{1}H-NMR spectroscopy, the integration curve provides information about

A. the number of neighbouring protons.

B. the splitting patterns.

C. the chemical shift values.

D. the relative number of protons in different environments.

Continues →

Question 2

Which of the following statements regarding peak splitting patterns in ^{1}H-NMR spectroscopy is correct?

A. The peak splitting pattern provides information about the number of neighbouring protons.

B. The peak splitting pattern is determined by the number of neighbouring carbon atoms.

C. The peak splitting pattern is independent of the number of neighbouring protons.

D. The peak splitting pattern is determined by the chemical shift values.

Question 3

Which of the following is **not** a valid application of the n + 1 rule in ^{1}H-NMR spectroscopy?

A. Determining the number of non-equivalent proton environments

B. Identifying the nature of neighbouring protons

C. Determining the chemical shift values

D. Analysing peak splitting patterns

Question 4

A compound shows a single peak in its ^{1}H-NMR spectrum. What can be concluded about the protons in the compound?

A. There are no neighbouring protons.

B. There are three neighbouring protons.

C. There are four neighbouring protons.

D. There are two neighbouring protons.

Theory summary

- Low resolution ^{1}H-NMR spectroscopy is used to obtain the following information about an organic compound:
  - the number of non-equivalent proton environments (equal to the number of distinct peaks)
  - the ratio of the number of protons in each of these types of environments (equal to the ratio of the heights of the integration curves)
  - the possible types of proton environments present (from the chemical shift values given in the VCE Data Book).
- Low resolution ^{1}H-NMR spectra do not show splitting patterns.
- High resolution ^{1}H-NMR spectroscopy is used to obtain all of the information provided by low resolution ^{1}H-NMR spectroscopy, as well as the number of protons in neighbouring proton environments.
- The n + 1 rule is used to describe the splitting patterns shown in high resolution ^{1}H-NMR spectroscopy, where the number of splits in a peak is equal to the number of protons in the neighbouring proton environment(s) (n) + 1.
- Equivalent proton environments combine, showing as one peak on a low resolution ^{1}H-NMR spectrum, or as a distinct set of peaks on a high resolution ^{1}H-NMR spectrum.

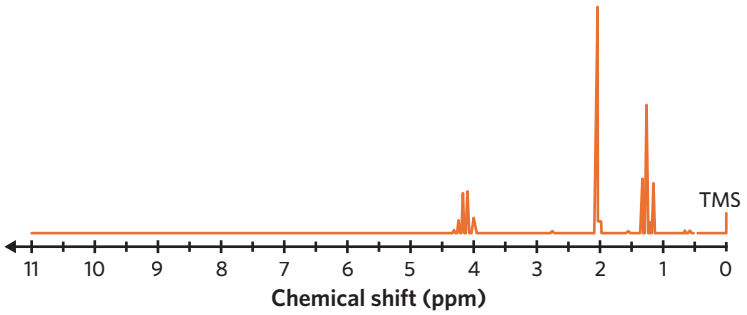
10D Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 5–7.

The ^{1}H-NMR spectrum of an unknown organic molecule is shown below.



Question 5 (1 MARK)

How many non-equivalent proton environments are present in the unknown organic compound?

A. 2

B. 3

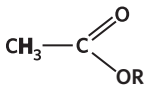
C. 4

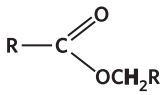
D. 5

Question 6 (1 MARK)

Which of the following types of proton environments could correspond to the peak at 2.0 ppm?

A. $R_3—CH$

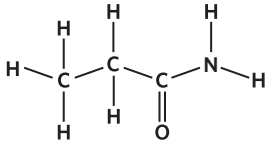
B. 

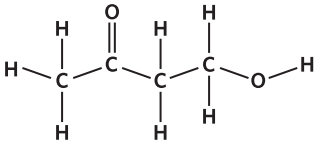
C. 

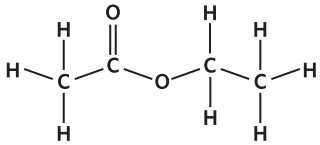
D. $R—CH_2—R$

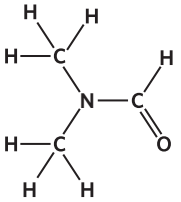
Question 7 (1 MARK)

Which one of the following is the unknown organic molecule?

A. 

B. 

C. 

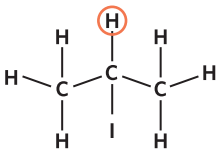
D. 

VCAA (NHT) 2022 exam Multiple choice Q28

Exam-style

Question 8 (1 MARK)

Consider the following organic compound.



On a ^{1}H-NMR spectrum, how many splits would appear in the set of peaks corresponding to the proton circled?

A. 1 **B.** 4 **C.** 6 **D.** 7

Question 9 (1 MARK)

The low resolution proton NMR spectrum for an unknown organic compound contains 4 sets of distinct peaks. The heights of the integration curves have a ratio of 3 : 2 : 2 : 1. The unknown organic compound could be

A. $CH_3CH_2CHCH_2$

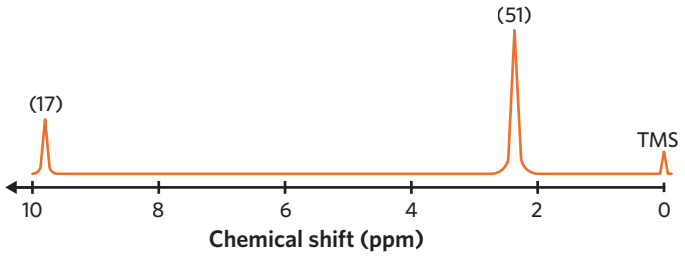
B. $CH_3CH_2CH_2CH_3$

C. $CH_3CH_2CH_2NH_2$

D. $CH_3COOCH_2CH_2CH_3$

Question 10 (5 MARKS)

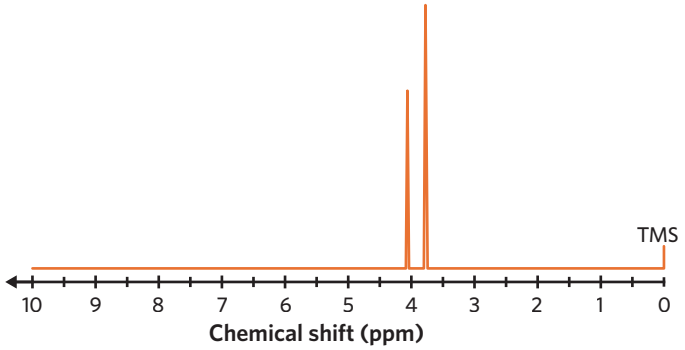
The low resolution proton NMR spectrum obtained from an organic compound with the molecular formula C_2H_4O is shown.



The areas beneath each peak are given on the spectrum. What is the IUPAC name of the organic compound responsible for the low resolution proton NMR spectrum shown? Justify your answer.

Question 11 (8 MARKS)

An unknown organic molecule with the molecular formula $C_3H_5O_2Cl$ produces the following high resolution ^{1}H-NMR spectrum. It is known that the compound is **not** a carboxylic acid.



The relative integration values for the two peaks are given in the following table.

Chemical shift (ppm)	4.1	3.7
Integration values	0.50	0.75

a. What information about the unknown organic compound is provided by the ^{1}H-NMR spectrum and integration value data? 3 MARKS

VCAA 2022 exam Short answer Q5d

b. Identify the types of proton environments responsible for each peak. Provide justifications for your answers. 4 MARKS

c. Draw a structure for the unknown organic molecule that is consistent with the information provided. 1 MARK

VCAA 2022 exam Short answer Q5e

Key science skills

Question 12 (4 MARKS)

Two VCE chemistry students, Jacob and Charbel, are discussing the use of low resolution and high resolution proton NMR. Jacob asserts that low resolution NMR is a more useful analytical technique as they find it easier to understand. Charbel disagrees, stating that high resolution proton NMR is more useful as more information is provided about the structure of the molecule being analysed.

a. Evaluate the scientific validity of Jacob's assertion. 2 MARKS

b. Evaluate the scientific validity of Charbel's statement. 2 MARKS

FROM LESSONS 12A & 12C

Question 13 (4 MARKS)

Proton nuclear magnetic resonance (NMR) spectroscopy can be used as both a qualitative and quantitative analytical technique.

a. Describe how proton NMR spectroscopy can be used as a qualitative analytical technique. 2 MARKS

b. Describe how proton NMR spectroscopy can be used as a quantitative analytical technique. 2 MARKS

FROM LESSON 12B

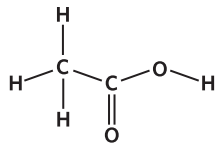
Questions from multiple lessons

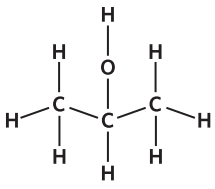
Question 14 (1 MARK)

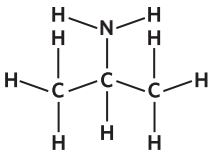
The spectroscopy information for an organic molecule is given in the following table.

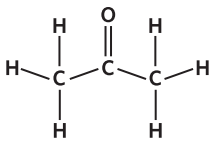
Number of peaks in ^{13}C-NMR	2
Number of sets of peaks in ^{1}H-NMR	3
m/z of the last peak in the mass spectrum	60
Infra-red (IR) spectrum	An absorption peak appears at 3350 cm^{-1}

The organic molecule is

A. 

B. 

C. 

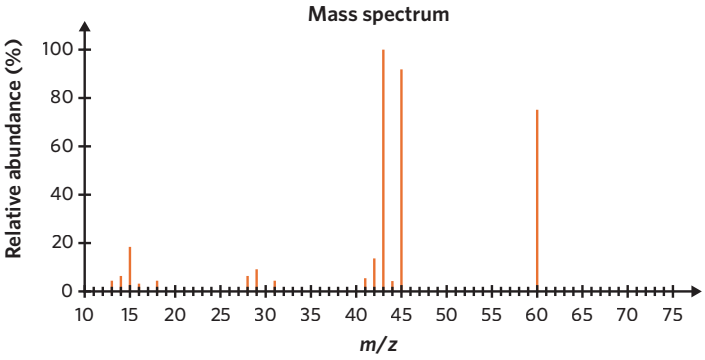
D. 

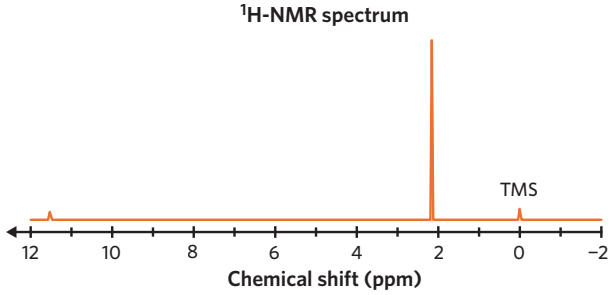
VCAA 2021 exam Multiple choice Q11

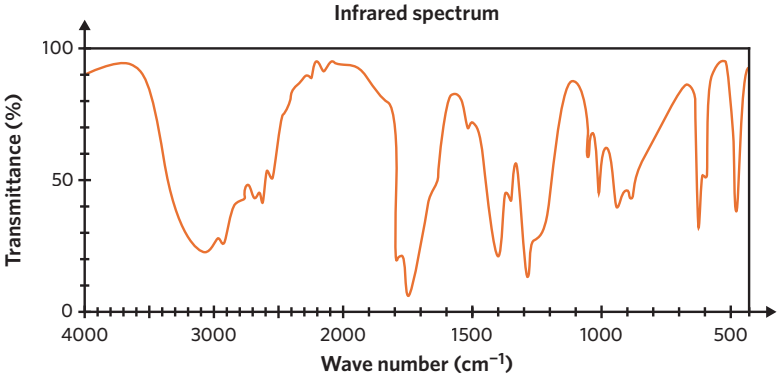
FROM LESSONS 10A, 10B & 10C

Question 15 (6 MARKS)

The structure of an organic molecule, with empirical formula CH_2O, is analysed using spectroscopic techniques. The mass spectrum, infrared spectrum, and high resolution ^{1}H-NMR spectrum for this molecule are given below.







Use the information provided by these spectra to answer the following questions.

a. What is the molecular formula of this molecule? Justify your answer with a calculation. 2 MARKS

b. How many different proton environments are there in this molecule? 1 MARK

c. Draw the structure of the unknown molecule, clearly showing all bonds. 1 MARK

d. Explain how the structure of the compound you have drawn in part **c** is consistent with its IR spectrum. 1 MARK

e. Name the compound you have drawn in part **c**. 1 MARK

VCAA 2009 Exam 1 Short answer Q5

FROM LESSONS 7A, 7B, 10A & 10B

Back to contents

10E Chromatography

STUDY DESIGN DOT POINT

- the principles of chromatography, including high performance liquid chromatography (HPLC) and the use of retention times and the construction of a calibration curve to determine the concentration of an organic compound in a solution (excluding features of instrumentation and operation)

10A 10B 10C 10D **10E** 10F

- 4.2.9.1 & 4.2.9.2 Principles of chromatography & HPLC
- 4.2.9.3 Analysing chromatograms

ESSENTIAL PRIOR KNOWLEDGE

- Polarity
- Solubility

See questions 85–86.



Image: sirtravelalot/Shutterstock.com

How is chromatography used to drug test athletes?

High performance liquid chromatography (HPLC) is employed to detect and quantify drug metabolites and prohibited substances in urine samples for anti-doping testing in sports. In this lesson, we will learn about the use of chromatography to separate substances, and determine their concentrations in samples using **calibration curves**.

KEY TERMS AND DEFINITIONS

Adsorption adhering of a component onto the stationary phase

Calibration curve a graphical representation of the relationship between the concentration of a substance and its corresponding response on a detector

Chromatogram visual output of chromatography

Desorption release of a component from the stationary phase by dissolving

Eluent solvent fluid that moves through a chromatography system

High performance liquid chromatography (HPLC) chromatography technique in which the mobile phase and sample are pumped through a tightly packed stationary phase under pressure

Interpolate infer values from a graph within the range of data

Miscibility ability of two or more substances to dissolve in each other

Mobile phase fluid in a chromatography system that carries the sample over the stationary phase

Origin line at which samples are placed in paper and thin-layer chromatography

Paper chromatography chromatography technique using absorbent paper

Peak area the area enclosed between the peak and the baseline on a chromatogram

Retention time (R_t) time taken for a component in a sample to pass through an HPLC column

Resolution (chromatography) degree of separation between two different peaks on a chromatogram

Stationary phase solid onto which the components of a sample adsorb

Thin-layer chromatography chromatography technique using a thin stationary phase supported by an inert backing

Principles of chromatography & HPLC 4.2.9.1 & 4.2.9.2

Chromatography is the process of separating components in a mixture based on their solubility.

How can substances be separated based on solubility?

Chromatography is an analytical technique used to separate the components of a sample. There are several different chromatography techniques used in laboratories today, ranging from relatively simple methods such as **paper chromatography** to more advanced methods such as high performance liquid chromatography (HPLC). In each of these techniques, the varying solubility of different substances is the key to identifying and quantifying the presence of certain compounds in a mixture.

In VCE chemistry Unit 1, we explored the effect of a compound's polarity on its solubility in different solvents. The most important rule to recall is that 'like dissolves like'; that is, if a solute has the same polarity as a solvent, then the solute will dissolve in that solvent. This means that polar compounds like water will dissolve compounds that are polar, but will not dissolve non-polar compounds. Similarly, non-polar compounds will dissolve compounds that are non-polar, but will not dissolve polar compounds. This is famously demonstrated by the lack of **miscibility** between oil (non-polar) and water (polar) (figure 1).



Image: Frennet Studio/Shutterstock.com

Figure 1 The immiscibility of oil and water

In chromatography, a solvent of known polarity – the **mobile phase** – is passed through a mixture over a medium of known polarity – the **stationary phase**. As the mobile phase passes through the mixture over the stationary phase, the components in the mixture undergo a continual process of **adsorption** to and **desorption** from the stationary phase. The polarity of the components in the mixture, the mobile phase, and the stationary phase will dictate how strongly each component adheres to the stationary phase, and how readily each component desorbs by redissolving in the mobile phase.

One of the cheapest chromatography techniques is paper chromatography, which involves the placing of highly absorbent paper (the stationary phase) in a solvent (the mobile phase). The solvent then dissolves the components of the sample to different degrees as it passes up the paper, separating the components of the sample (figure 2). **Thin-layer chromatography** (TLC) is a very similar technique; however, the stationary phase is instead a thin layer of adsorbent material such as aluminium oxide, cellulose, or silica gel covering a glass or plastic plate. This form of stationary phase allows for much stronger polarity (aluminium oxide or silica gel) or non-polarity (cellulose).

MISCONCEPTION

'The mobile phase bonds to the stationary phase.'

Mobile polar molecules are attracted to a non-polar stationary phase through intermolecular forces, not intramolecular bonds.

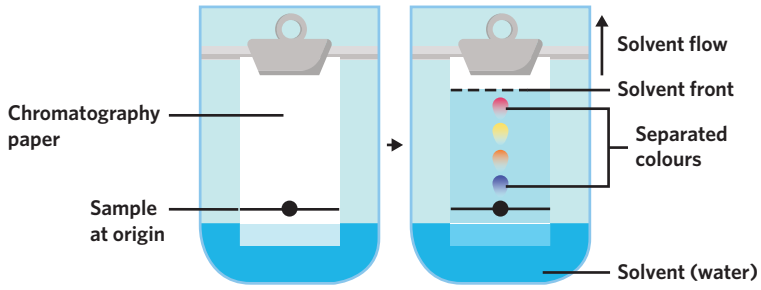


Figure 2 Paper chromatography setup

As shown in figure 2, the sample being analysed is placed at the **origin**. As the solvent – in this case, water – passes through the chromatography paper, the components of the mixture migrate through the stationary phase to different extents. Given water is a polar substance, the pink component must be the most polar of the four components as it has migrated furthest up the paper, and hence must dissolve most readily in water. On the other hand, since the blue component has migrated the least distance, it must be the least polar component in the sample, desorbing from the stationary phase to the smallest extent.

KEEN TO INVESTIGATE?

1 **How was chromatography first used?**
Search: Who is Mikhail Tsvet?
Chromatography today

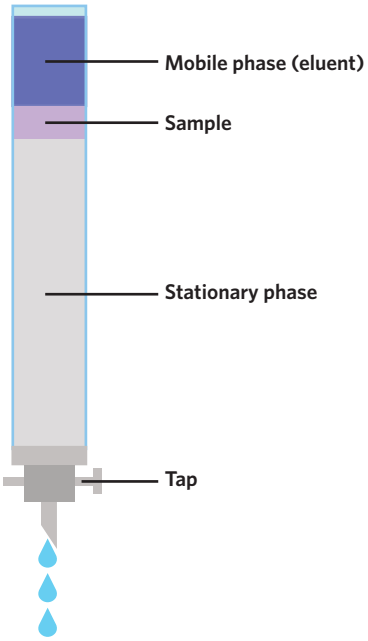


Figure 3 Column chromatography setup

How do the principles of chromatography apply in more sensitive techniques?

Column chromatography is a more sensitive technique for the analysis of the components in a sample. In column chromatography, the sample to be analysed is placed at the top of a glass column containing a solid stationary phase, followed by an **eluent**, or solvent. The first component of the sample to pass through, or elute from, the column is the one that has adhered least strongly to the stationary phase, and is hence the component with a polarity closest to the polarity of the solvent. Since the components will migrate down the column at varying rates, the components of a mixture can be physically separated and collected by the control of a tap at the bottom of the column (figure 3).[1]

High performance liquid chromatography (HPLC) is another sensitive application of chromatographic principles. In HPLC, a column or coil is packed tightly with a stationary phase and a solvent is allowed to pass through. However, HPLC is much more sensitive than the other techniques mentioned as the particles used in the stationary phase are approximately 20 times smaller, resulting in more frequent adsorption and desorption of the components in a sample. Hence, samples composed of many components of similar polarity can be better separated. Figure 4 shows a standard HPLC setup.

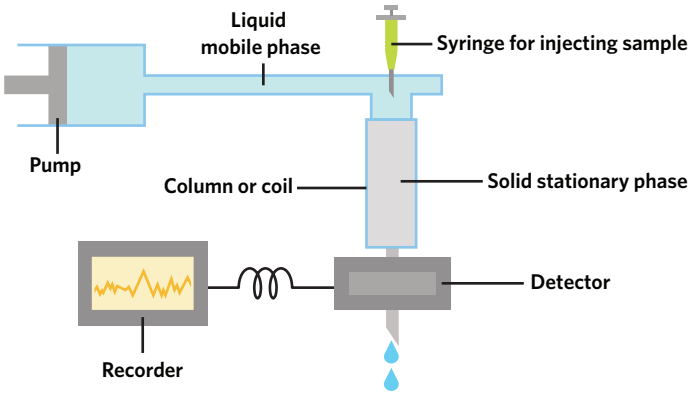


Figure 4 High performance liquid chromatography setup

Given the particles in the stationary phase are significantly smaller than in column chromatography, the mobile phase and sample experience much greater resistance as they pass through. To counteract this resistance, a pump is used to create a pressurised environment inside the column, thereby forcing the mobile phase and sample through the column. After passing through the stationary phase, the components are typically detected based on UV light absorption.

PROGRESS QUESTIONS

Question 1

In chromatography, components of a sample

A. adsorb to the mobile phase only once and dissolve into the stationary phase only once.

B. dissolve into the mobile phase only once and adsorb to the stationary phase only once.

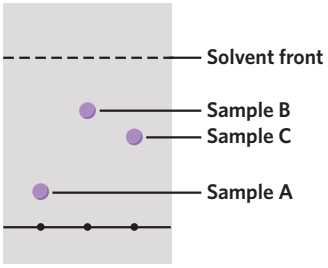
C. are continuously adsorbing to the mobile phase and dissolving into the stationary phase.

D. are continuously dissolving into the mobile phase and adsorbing to the stationary phase.

Continues →

Question 2

The thin layer chromatography plate shown has a polar stationary phase. It was developed using hexane as the solvent.



Which sample is the most polar?

A. Sample A

B. Sample B

C. Sample C

D. There is not enough information to determine which sample has the most polar molecules.

VCAA 2013 exam Multiple choice Q7

Analysing chromatograms 4.2.9.3

Chromatograms obtained from chromatography can be used to determine the concentration of a particular substance in a sample.

How can chromatography be used to determine the concentration of an organic compound?

The output of high performance liquid chromatography is a chromatogram of absorbance peaks (figure 5).

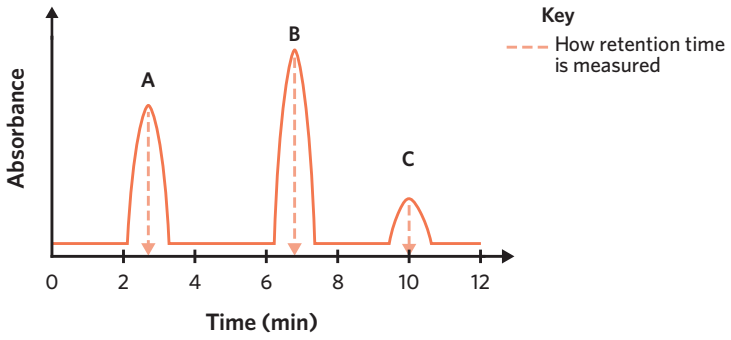


Figure 5 Chromatogram of a sample containing 3 components

In HPLC, the time taken for a component to pass through the column or coil and reach the detector is known as the **retention time**, R_t. The R_t value for a component in a sample can be compared against R_t values of known substances obtained under identical conditions to identify the specific components present in a sample. However, variables such as temperature, the type of stationary phase, the type of mobile phase, and the pressure in the column all need to be considered when comparing experimentally obtained R_t values to those of known substances. If any of these variables are different, the R_t value is likely to change. Table 1 outlines the expected effects of changing experimental conditions on retention times.

USEFUL TIP

An important step in HPLC is the initial calibration of the instrument under the given conditions to ensure the results being obtained align with known retention times of substances being analysed.

MISCONCEPTION

'Only molecular size/relative molecular mass and attraction to the stationary phase affect retention time.'

In addition to molecular size/relative molecular mass and attraction to the stationary phase, the attraction to the mobile phase also affects retention time.

Table 1 The expected effect of a change to conditions on retention time

Change to conditions	Effect on retention time, R_t
Increased length of column or coil	Increase
Increased temperature	Decrease
Increased total surface area of stationary phase	Increase

An HPLC chromatogram can also be used to provide quantitative information about the concentration of the components in a sample. The **peak area** – the area under a peak in an HPLC chromatogram – is proportional to the amount of the substance responsible for the peak present in the sample. Once a component in a sample has been identified using its retention time, the following steps are implemented to construct a calibration curve and determine the concentration at which the component is present.

1. Several solutions of the component at known concentrations are run through the same HPLC column under identical conditions.
2. The resulting peak areas are then plotted against concentration and a calibration curve is drawn.
3. The concentration of the component in the sample is **interpolated** from the calibration curve using construction lines.

For example, the retention time of compound C in figure 5 is found to correspond to glucose, and the area underneath the peak corresponding to peak C is 0.450 mm^2. Glucose standard solutions at concentrations of 1.00 mg L^{-1}, 2.00 mg L^{-1}, 3.00 mg L^{-1}, 4.00 mg L^{-1} and 5.00 mg L^{-1} are all run through the same HPLC column that produced the chromatogram in figure 5. The peak areas recorded are given in table 2, and are then plotted against concentration on the calibration curve shown in figure 6.

Table 2 Peak areas for glucose solutions of known concentration

Glucose concentration (mg L^{-1})	Peak area (mm^2)
1.00	0.0600
2.00	0.170
3.00	0.330
4.00	0.390
5.00	0.510

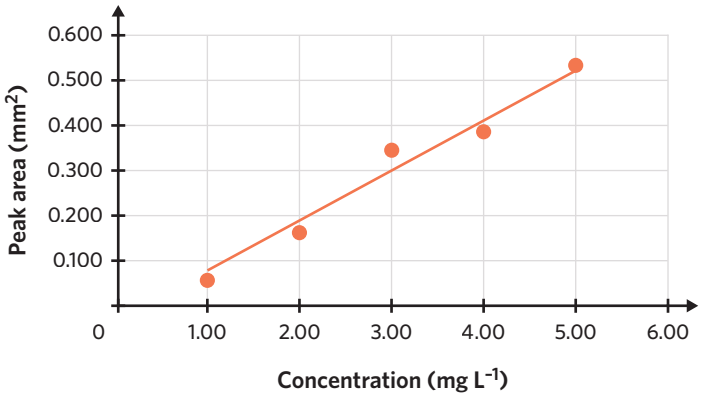


Figure 6 Calibration curve of glucose standard solutions

USEFUL TIP

The use of retention times to identify the presence of substances in a sample is qualitative analysis, whilst the use of peak areas to identify the concentration of substances in a sample is quantitative analysis.

Given the peak area for glucose in the sample is 0.450 mm^2, we can use the calibration curve to estimate the concentration of glucose in the sample (figure 7).

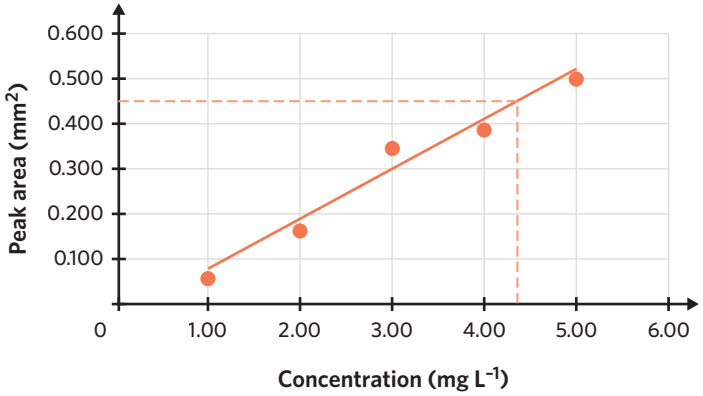


Figure 7 Interpolating the concentration of glucose in the sample using construction lines

In figure 7, it is shown that a peak area of 0.450 mm^2 corresponds to a concentration of 4.4 mg L^{-1}. Hence, the concentration of glucose in the sample is 4.4 mg L^{-1}.

USEFUL TIP

Whilst extrapolation (estimating outside the range of data) can be used to determine unknown concentrations of components in a sample, it is generally considered to be a relatively inaccurate result. In these cases, dilutions are required so the value can be interpolated.

WORKED EXAMPLE 1

Consider the following changes that could be applied to the operating parameters for a high performance liquid chromatography (HPLC) setup with a polar stationary phase and a non-polar mobile phase:

I. Decreasing the viscosity of the mobile phase

II. Using a more tightly packed stationary phase

III. Using a mobile phase that is more polar than the stationary phase.

Which of the changes would be most likely to reduce the retention time of ethanol in the HPLC?

A. I only

B. I and III only

C. III only

D. II and III only

What information is presented in the question?

The HPLC setup has a polar stationary phase and a non-polar mobile phase.

Three changes could be applied to the operating parameters for the HPLC setup.

What is the question asking us to do?

Determine which of the three changes will result in a shorter retention time for an alcohol.

What strategies do we need in order to answer the question?

1. Identify the effect of decreasing the viscosity of the mobile phase on retention time of components.
2. Identify the effect of the stationary phase's packing on retention time of components.
3. Identify whether ethanol will dissolve more readily in a non-polar or polar mobile phase.

Answer

Decreasing the viscosity allows the mobile phase to pass through the column more quickly, so dissolved ethanol will also pass through more quickly, thereby reducing retention time.

Packing the stationary phase more tightly will make it more difficult for the mobile phase to pass through the column, so dissolved ethanol will pass through more slowly, thereby increasing retention time.

Ethanol is polar due to the presence of a hydroxyl group, so it will dissolve more readily in a polar mobile phase. Hence, the use of a mobile phase that is more polar than the stationary phase will allow ethanol to pass through more quickly, thereby reducing retention time.

Therefore, changes I and III are correct, so the correct option is B.

VCAA 2020 exam Multiple choice Q20

KEEN TO INVESTIGATE?

[2] **How is chromatography used to test for banned substances in athletes?**
Search YouTube: Brian Cox Short Films – Chromatography

HPLC has many experimental applications in fields such as medical analysis.[2] As such, it is important that the results obtained from an HPLC instrument provide useful information. One way to ensure useful information is obtained is by ensuring that the peaks on a chromatogram do not overlap, which can otherwise cause measurement errors. This is done by increasing the **resolution** (the distance between distinct peaks on a chromatogram) through techniques such as increasing the length of the column, changing the temperature, or changing either of the mobile or stationary phases. Each of these methods allows for better separation of the components of a given sample.

PROGRESS QUESTIONS

Question 3

Which of the following changes is most likely to result in faster elution (lower retention time) of a component in an HPLC column?

A. Decreased temperature
B. Increased column length
C. Increased temperature
D. Decreased size of stationary phase particles

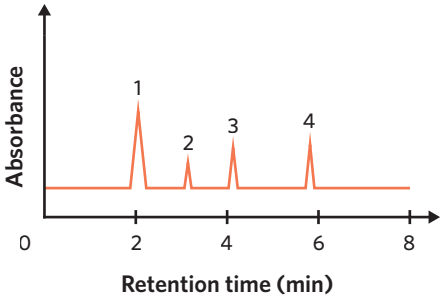
Question 4

When comparing experimentally obtained retention times to known retention times, which of the following HPLC conditions must be identical?

A. Temperature inside the column
B. Pressure inside the column
C. Type of mobile phase
D. All of the above

Question 5

A mixture containing 4 primary alcohols was separated using high performance liquid chromatography with a non-polar stationary phase and a polar mobile phase. Each alcohol contained only one hydroxyl functional group. The resulting chromatogram is shown.



According to the chromatogram,

A. alcohol 1 has the highest retention time.
B. alcohol 2 would elute from the column first.
C. alcohol 3 is closest in polarity to the stationary phase.
D. alcohol 4 has the highest molar mass.

Continues →

Question 6

A particular HPLC instrument was used to separate mixtures of two chemicals. Each separation was done under similar conditions. The mobile phase used was either water or hexane, and the same stationary phase was used for each separation. For the mobile phase given in the first column, which one of the following options gives the two chemicals expected to have the largest difference in retention time?

	Mobile phase	Chemicals in the mixtures
A.	Hexane	Butanoic acid, butane
B.	Water	Ethanoic acid, ethanol
C.	Hexane	Ethanol, methanol
D.	Water	Butane, octane

VCAA (NHT) 2019 exam Multiple choice Q24

Theory summary

- Chromatography is used to separate substances based on their solubility.
- Polar compounds dissolve in polar solvents, whilst non-polar compounds dissolve in non-polar solvents.
- In chromatography, the components of a sample are continuously dissolving into the mobile phase and adsorbing to the stationary phase.
- In column chromatography and HPLC, the component that elutes most quickly is the component with a polarity closest to that of the mobile phase.
- In HPLC, the retention time of a substance is the time taken for the substance to pass through the column which can be influenced by:
  - molecular size/relative molecular mass
  - attraction to the stationary phase
  - attraction to the mobile phase.
- The steps to determine the concentration of a substance in a sample are as follows:
  1. Several solutions of the component at known concentrations are run through the same HPLC column under identical conditions.
  2. The resulting peak areas are then plotted against concentration and a calibration curve is drawn.
  3. The concentration of the component in the sample is then interpolated from the calibration curve.

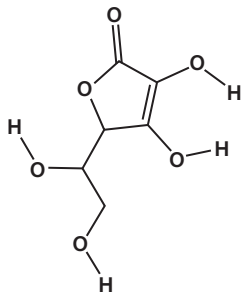
10E Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 7–9.

A high-performance liquid chromatography (HPLC) instrument is set up with a non-polar stationary phase and a polar mobile phase. It is used to analyse a liquid mixture containing three compounds: octane, heptanol, and vitamin C. The structure of vitamin C is given.



Question 7 (1 MARK)

Which of the compounds would pass through the HPLC column most quickly and why?

A. Octane, because it is the most polar compound

B. Octane, because it is the most non-polar compound

C. Vitamin C, because it is the most polar compound

D. Vitamin C, because it is the most non-polar compound

Question 8 (1 MARK)

Which of the compounds would pass through the HPLC column most slowly and why?

A. Heptanol, because it is the most polar compound

B. Heptanol, because it is the most non-polar compound

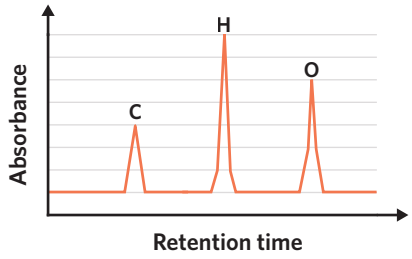
C. Octane, because it is the most polar compound

D. Octane, because it is the most non-polar compound

Question 9 (1 MARK)

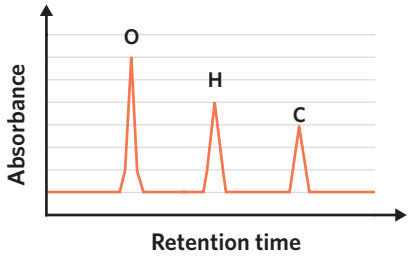
Which one of the following best represents the chromatogram that would be produced?

A.



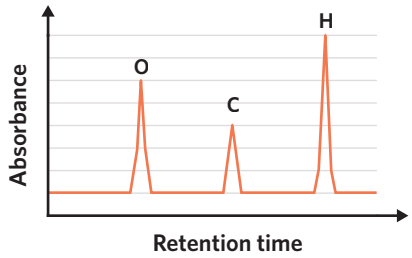
Key
C = Vitamin C
H = Heptanol
O = Octane

B.



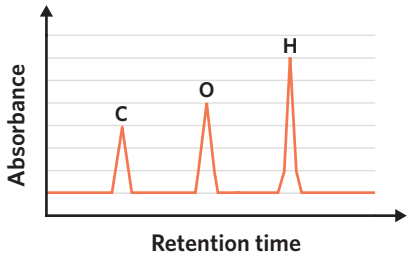
Key
C = Vitamin C
H = Heptanol
O = Octane

C.



Key
C = Vitamin C
H = Heptanol
O = Octane

D.



Key
C = Vitamin C
H = Heptanol
O = Octane

Exam-style

Question 10 (1 MARK)

Consider the following statements about a high-performance liquid chromatography (HPLC) column that uses a polar solvent and a non-polar stationary phase to analyse a solution:

I. Polar molecules in the solution will be attracted to the solvent particles by dipole-dipole attraction.

II. Non-polar molecules in the solution will be attracted to the stationary phase by dispersion forces.

III. Polar molecules in the solution will travel through the HPLC column more rapidly than non-polar molecules.

Which of these statements are true?

A. I and II only

B. I and III only

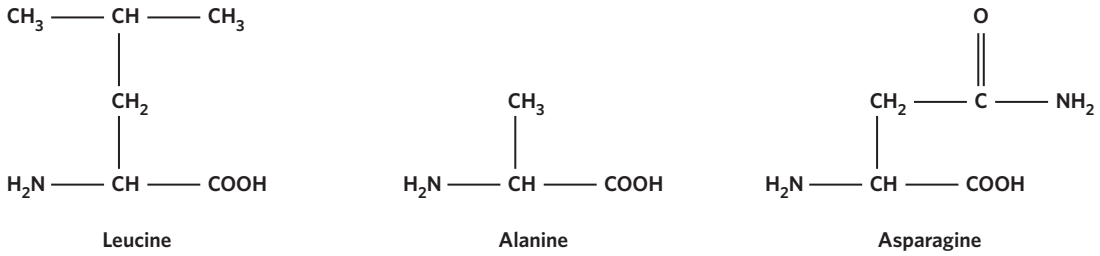
C. II and III only

D. I, II and III

VCAA 2015 exam Multiple choice Q8

Question 11 (1 MARK)

A high-performance liquid chromatography (HPLC) instrument is set up with a polar mobile phase and a non-polar stationary phase. Three amino acids – leucine, Leu, alanine, Ala, and asparagine, Asn – are added to the mobile phase and are run through the HPLC instrument.



The order of the retention times, from shortest to longest, for these three amino acids is

A. Leu, Ala, Asn.

B. Leu, Asn, Ala.

C. Ala, Asn, Leu.

D. Asn, Ala, Leu.

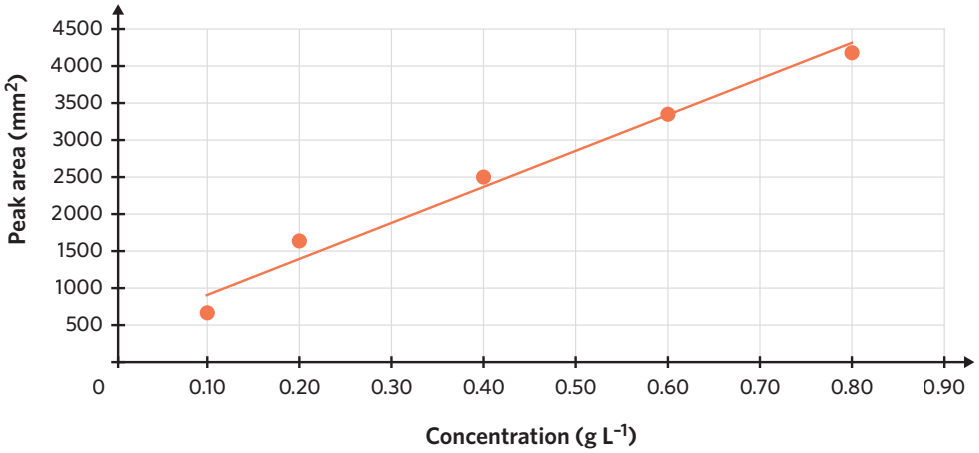
VCAA 2022 exam Multiple choice Q24

Question 12 (6 MARKS)

High-performance liquid chromatography (HPLC) was used to determine the sucrose concentration in a sample taken from a can of soft drink. Standard solutions were made up using pure sucrose and deionised water. A 1 mL sample of each standard solution was injected into the HPLC column and its peak area was recorded, as shown in the table below.

Concentration of sucrose ($g\ L^{-1}$)	Peak area (mm^2)
0.10	700
0.20	1600
0.40	2500
0.60	3300
0.80	4200

The experimental results (shown as dots) and a calibration line of the concentration of sucrose against peak area are shown in the graph below.



A 5.0 mL sample of the soft drink was diluted to 100 mL in a volumetric flask. A 10.0 mL aliquot of this solution was transferred to a 250 mL volumetric flask and filled up to the calibration mark using deionised water. A sample of this solution was injected into the HPLC column. The peak area of the sample solution at the same retention time and under the same conditions as those used to determine the calibration line was found to be 1900 mm^2.

a. Determine the sucrose content of the sample tested in the HPLC, in grams per litre. 1 MARK

b. The can used to obtain the sample contained 330 mL of soft drink. Assuming that the only sugar in the soft drink is sucrose, calculate the mass of sucrose in the can of soft drink. 4 MARKS

c. In the analysis described above, the retention time of sucrose was 2.5 minutes. One change was made to the HPLC setup and the sample was run through the column again. The retention time of sucrose increased to 4 minutes. Suggest a possible change that could have been made to cause this increase. 1 MARK

Adapted from VCAA 2019 exam Short answer Q5a

Key science skills

Question 13 🌶🌶🌶 (9 MARKS)

Aspartame is an ingredient in some soft drinks. Aspartame is unstable in some conditions and reacts to form four main products. One of the products of aspartame breakdown is 5-benzyl-3,6-dioxo-2-piperazineacetic acid (DKP). It is thought that DKP may be harmful to humans.

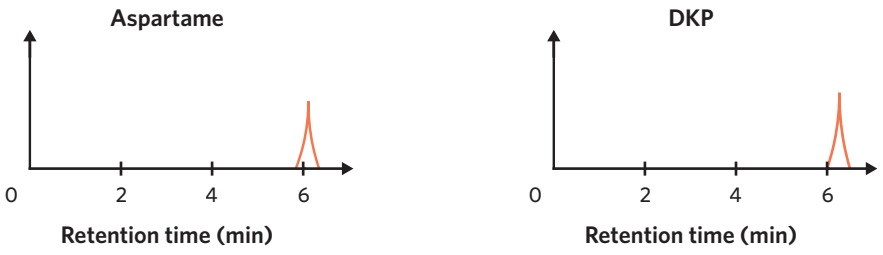
A student, Bence, investigates the effect of storage temperature on the rate of production of DKP from aspartame in lemonade. Experimental data is obtained using high-performance liquid chromatography (HPLC) to analyse the aspartame and DKP content in lemonade samples.

HPLC calibration

Bence first calibrated the HPLC using the following method:

1. Prepare and refrigerate a standard solution of pure aspartame with a concentration of 1000 mg L^{-1}.
2. Transfer a 10.00 mL aliquot of the pure aspartame solution into a 1.000 L volumetric flask.
3. Fill the volumetric flask up to the 1.000 L mark with deionised water and shake the flask.
4. Inject a sample of the diluted aspartame solution into the HPLC to obtain a chromatogram.
5. Repeat steps 1–4 with DKP.

The following two calibration chromatograms were obtained.



Analysis of lemonade samples

Bence then followed the method given in steps 6–14 to investigate the rate of production of DKP from aspartame in lemonade at different storage temperatures.

6. Open a can of lemonade.

7. Transfer a 10.00 mL aliquot of lemonade from the can into a 1.000 L volumetric flask.

8. Fill the volumetric flask up to the 1.000 L mark with deionised water and shake the flask.

9. Inject a sample of the diluted lemonade into the HPLC using the same operating conditions used during calibration.

10. Set up three water baths at temperatures of 15 °C, 25 °C, and 35 °C.

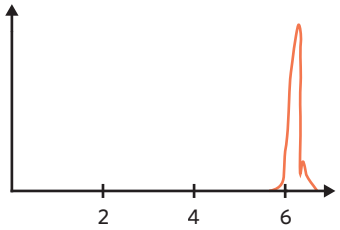
11. Put three unopened cans of lemonade into each of the three water baths.

12. After one day, take one can from each water bath and follow steps 6–9.

13. After two days, take one can from each water bath and follow steps 6–9.

14. After three days, take one can from each water bath and follow steps 6–9.

One of the chromatograms from the diluted lemonade is given below.



Retention time (min)

a. What is the dependent variable of Bence's investigation? 1 MARK

b. What steps, in addition to steps 1–14, need to be taken to use the HPLC data to measure the dependent variable? 3 MARKS

c. State a change to the operating conditions of the HPLC that could be made to reduce the errors in measuring the concentrations of aspartame and DKP. 1 MARK

d. State how the change from part **c** would reduce the measurement errors. 1 MARK

e. Bence found that the can of lemonade tested at the beginning of the experiment contained:

- 0.00178 M aspartame
- 0.00045 M DKP

Bence quantified the remaining data from the HPLC and prepared the following table.

Storage temperature	Concentration after one day (M)		Concentration after two days (M)		Concentration after three days (M)	
	Aspartame	DKP	Aspartame	DKP	Aspartame	DKP
15 °C	0.00179	0.00043	0.00175	0.00042	0.00176	0.00041
25 °C	0.00175	0.00044	0.00172	0.00046	0.00171	0.00063
35 °C	0.00160	0.00051	0.00155	0.00049	0.00154	0.00058

Write a conclusion based on the results given in the table above. 1 MARK

f. Identify a variable that has not been controlled. 1 MARK

g. Explain how the variable identified in part **f** affects the validity of the experiment. 1 MARK

VCAA 2021 exam Short answer Q9

FROM LESSONS 12A, 12B, 12C, 12D & 12E

Questions from multiple lessons

Question 14 🌶🌶🌶 (13 MARKS)

Biodiesel is a mixture of fatty acid methyl esters. The following table lists the names and formulas of several common fatty acids.

Name	Formula	Semi-structural formula
Lauric	$C_{11}H_{23}COOH$	$CH_3(CH_2)_{10}COOH$
Myristic	$C_{13}H_{27}COOH$	$CH_3(CH_2)_{12}COOH$
Palmitic	$C_{15}H_{31}COOH$	$CH_3(CH_2)_{14}COOH$
Palmitoleic	$C_{15}H_{29}COOH$	$CH_3(CH_2)_4CH_2CH{=}CHCH_2(CH_2)_5CH_2COOH$
Stearic	$C_{17}H_{35}COOH$	$CH_3(CH_2)_{16}COOH$
Oleic	$C_{17}H_{33}COOH$	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$

A particular triglyceride used in the manufacture of biodiesel was analysed by reacting it with excess methanol and a potassium hydroxide catalyst. This reaction produced fatty acid methyl esters and glycerol. At the conclusion of the reaction, two liquid layers were observed in the reaction vessel. The bottom layer was an aqueous solution.

a. Other than water, name **one** substance that would be found in the aqueous layer. Justify your answer. 2 MARKS

b. The top layer is a non-aqueous mixture. It was separated from the aqueous layer and then purified. The non-aqueous layer was found to contain the fatty acid methyl esters. A small sample of the purified ester mixture was passed through a chromatograph attached to a mass spectrometer.

The chromatogram showed two peaks, indicating that the ester mixture contained two different fatty acid methyl esters, A and B. The peak area of each compound and the mass-to-charge ratio of the molecular ion of each compound are shown in the following table. Assume that the charge on each molecular ion is +1.

Methyl ester	Peak area	Mass-to-charge ratio of the molecular ion
A	1000	270
B	2000	298

What information about the relative amounts of the two methyl esters is provided by the chromatogram? 1 MARK

c. The mass spectrum of methyl ester A corresponds to that of methyl palmitate, $CH_3(CH_2)_{14}COOCH_3$. What is the name and semi-structural formula of methyl ester B? (Refer to the tables provided.) 2 MARKS

d. Use the information provided to draw a structure of the triglyceride. Use semi-structural formulas to represent the fatty acid residues. 3 MARKS

e. A weighed sample of methyl palmitate, $C_{17}H_{34}O_2$, was burnt in excess oxygen under a calorimeter. The experimental results are shown in the following table.

Mass of methyl palmitate	2.28 g
Temperature rise	1.18 °C
Calorimeter constant (calibration factor)	42.4 kJ $°C^{-1}$
$M(C_{17}H_{34}O_2)$	270.0 g mol^{-1}

i. Use the data provided to calculate the molar enthalpy of combustion of the methyl palmitate. 3 MARKS

ii. Write a balanced **thermochemical** equation for the combustion reaction. 2 MARKS

VCAA 2015 exam Short answer Q9

FROM LESSONS 1D, 2B, 8A & 10A

10F Combining techniques



Image: VanderWolf Images/Shutterstock.com

How can pollutants in our atmosphere be identified?

By combining the results from mass spectrometry, gas chromatography, and infrared spectroscopy, the identities and concentrations of pollutants in the air we breathe can be determined. In this lesson, we will learn about how to deduce the structures of simple organic compounds using a combination of laboratory and instrumental analysis techniques. We will also discuss how these techniques can be used to identify the presence and purity of organic compounds in mixtures and in isolation.

KEY TERMS AND DEFINITIONS

LC-MS combined use of liquid chromatography and mass spectrometry

STUDY DESIGN DOT POINTS

- deduction of the structures of simple organic compounds using a combination of mass spectrometry (MS), infrared spectroscopy (IR), proton nuclear magnetic resonance (^{1}H-NMR) and carbon-13 nuclear magnetic resonance (^{13}C-NMR) (limited to data analysis)
- the roles and applications of laboratory and instrumental analysis, with reference to product purity and the identification of organic compounds or functional groups in isolation or within a mixture

10A 10B 10C 10D 10E 10F

4.2.10.1 Deducing structures of organic compounds

4.2.11.1 Purity and identification of organic compounds

ESSENTIAL PRIOR KNOWLEDGE

7A Structures of organic compounds

See question 87.

Deducing structures of organic compounds 4.2.10.1

Typically, the use of only one instrumental analysis technique cannot provide definitive information about organic structures. However, the data obtained from using multiple instrumental analysis techniques together can be combined to deduce the exact structure of simple organic compounds.

How can instrumental analysis techniques be combined to deduce the structures of organic compounds?

In lessons 10A, 10B, 10C, and 10D, we learned about four different instrumental analysis techniques. The common thread within each technique is that, when used in isolation, there is not enough information obtained from the results to precisely determine the structure of an organic compound. However, when we combine the information obtained from multiple techniques, we can make more definitive conclusions about organic structures. Table 1 summarises the pieces of information that can be obtained from each analytical technique.

USEFUL TIP

When confronted with a question requiring the combination of multiple techniques, the compound you must identify can contain more than one functional group.

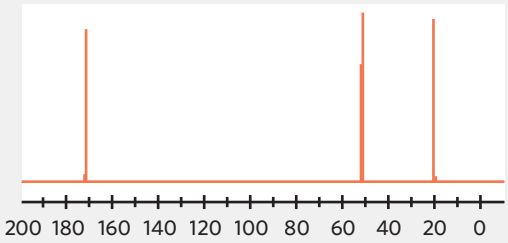
Table 1 Information provided by each instrumental analysis technique

Technique	Information provided
Mass spectrometry	• Molar mass • Possible branching patterns
Infrared spectroscopy	• Functional groups present
^{13}C-NMR	• Number of non-equivalent carbon environments • Types of carbon environments present
^{1}H-NMR	• Number of non-equivalent proton environments • Ratio of protons in each environment • Types of proton environments present • Number of protons in neighbouring proton environments

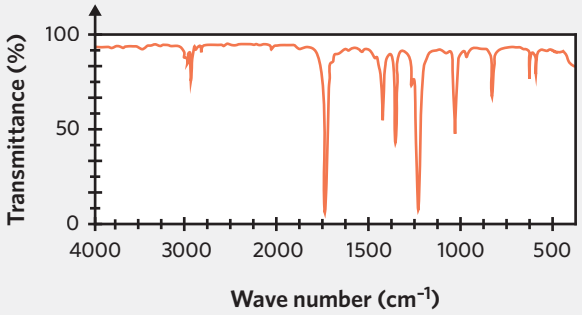
WORKED EXAMPLE 1

The following two spectra were obtained for a pure organic substance, Compound W.

^{13}C-NMR spectrum



Infra-red spectrum



The formula of compound W that is consistent with the spectra shown is

A. $CH_2(OH)CH_2CH_2OH$
B. CH_3CH_2COOH
C. CH_3COOCH_3
D. CH_3COCH_3

What information is presented in the question?

The ^{13}C-NMR spectrum and infrared spectrum from the spectral analysis of compound W.

What is the question asking us to do?

Determine which of the semi-structural formulas is consistent with the spectra given.

What strategies do we need in order to answer the question?

1. Identify the information provided by the ^{13}C-NMR spectrum.
2. Identify the information provided by the IR spectrum.
3. Combine both sets of information to deduce the compound consistent with the spectra.

Answer

The 3 peaks in the ^{13}C-NMR spectrum indicate that the compound contains 3 non-equivalent carbon environments. The IR spectrum indicates the presence of a C=O bond and the lack of an O—H (acid) or O—H (alcohol) bond.

Option A: $CH_2(OH)CH_2CH_2OH$ contains an O—H (alcohol) bond, which is not consistent with the IR spectrum, so option A is incorrect.

Option B: CH_3CH_2COOH contains an O—H (acid) bond, which is not consistent with the IR spectrum, so option B is incorrect.

Option C: CH_3COOCH_3 contains 3 non-equivalent carbon environments, which is consistent with the ^{13}C-NMR spectrum. CH_3COOCH_3 also contains a C=O bond, which is consistent with the IR spectrum. Therefore, option C is correct.

Option D: CH_3COCH_3 contains only 2 non-equivalent carbon environments, which is not consistent with the ^{13}C-NMR spectrum, so option D is incorrect.

VCAA (NHT) 2018 exam Multiple choice Q14

PROGRESS QUESTIONS

Question 1

A researcher uses a combination of spectroscopic techniques to determine the structure of a molecule.

Which combination of spectroscopic techniques provides the most information about the molecule's functional groups and number of carbon environments?

A.	Mass spectrometry	^{13}C-NMR
B.	Infrared	^{13}C-NMR
C.	Infrared	Mass spectrometry
D.	Mass spectrometry	^{1}H-NMR

VCAA (NHT) 2019 exam Multiple choice Q10

Purity and identification of organic compounds 4.2.11.1

Laboratory and instrumental analysis are essential tools in chemistry for determining the composition and structure of organic compounds.

How can analysis techniques be used to determine the purity of a sample?

In chapter 10, we explored 6 different techniques used in the analysis of organic compounds and mixtures containing organic compounds. Each of these techniques can be used to provide information about the purity of substances (table 2).

Table 2 Use of analytical techniques to assess purity of substances

Technique	Use in assessing purity
Mass spectrometry	The purity of a sample can be estimated by analysing the mass spectrum produced. Any peaks shown on the spectrum that do not correlate to the molecular ion or the possible fragment ions indicate the presence of additional compounds.
Infrared (IR) spectroscopy	The purity of a sample can be estimated by comparing the IR spectrum of the sample to that of a known pure sample. A pure product should exhibit characteristic absorption peaks corresponding to specific functional groups without any additional peaks.
Low resolution ^{13}C-NMR spectroscopy	The purity of a sample can be estimated by analysing the ^{13}C-NMR spectrum produced. A pure product should show a single peak for each non-equivalent carbon environment in the compound. The presence of additional peaks may indicate impurities or different chemical species.
Low resolution ^{1}H-NMR spectroscopy	Like low resolution ^{13}C-NMR, low resolution ^{1}H-NMR provides less detailed information but can still help in assessing purity. In a pure product, each unique proton environment should give rise to a single peak. Additional peaks may signify impurities or other compounds.

Continues →

Table 2 Continued

Technique	Use in assessing purity
High resolution ^{1}H-NMR spectroscopy	High-resolution ^{1}H-NMR spectroscopy is a powerful tool for identifying and quantifying impurities in a sample. A pure product will exhibit sharp and well-resolved peaks corresponding to each non-equivalent proton environment in the molecule. The presence of additional peaks or broadening of peaks may indicate impurities.
Chromatography	High performance liquid chromatography (HPLC) and gas chromatography (GC) are commonly employed for purity analysis. By comparing the chromatogram of the sample to that of known pure substances, one can assess the purity of the product. A pure product should display a single, sharp peak, while impurities will appear as additional peaks on the chromatogram.

In many cases, several of the analysis techniques listed in table 2 will be used in conjunction with each other to provide a more comprehensive analysis of the purity of a sample. These techniques or combinations of techniques are used in the pharmaceutical and petrochemical industries to identify the purity of products.

MISCONCEPTION

'The techniques in table 2 can be used to quantify the purity of a substance.'

The use of each technique in table 2 to test for purity is a from of qualitative analyses, as each only provides information about whether impurities are present in a product, not how much of an impurity is present.

Pharmaceutical applications

Laboratory and instrumental analysis play a crucial role in the pharmaceutical industry to ensure the safety and efficacy of drugs. Chemists utilise various analytical techniques to verify the purity of active pharmaceutical ingredients and detect impurities that might adversely affect the product's performance. For example, quality control laboratories use a combination of HPLC and mass spectrometry, often abbreviated to **LC-MS**. The HPLC phase can be used to detect for the presence of impurities, and mass spectrometry can be used to determine the relative abundance of any impurities in the sample (figure 1).

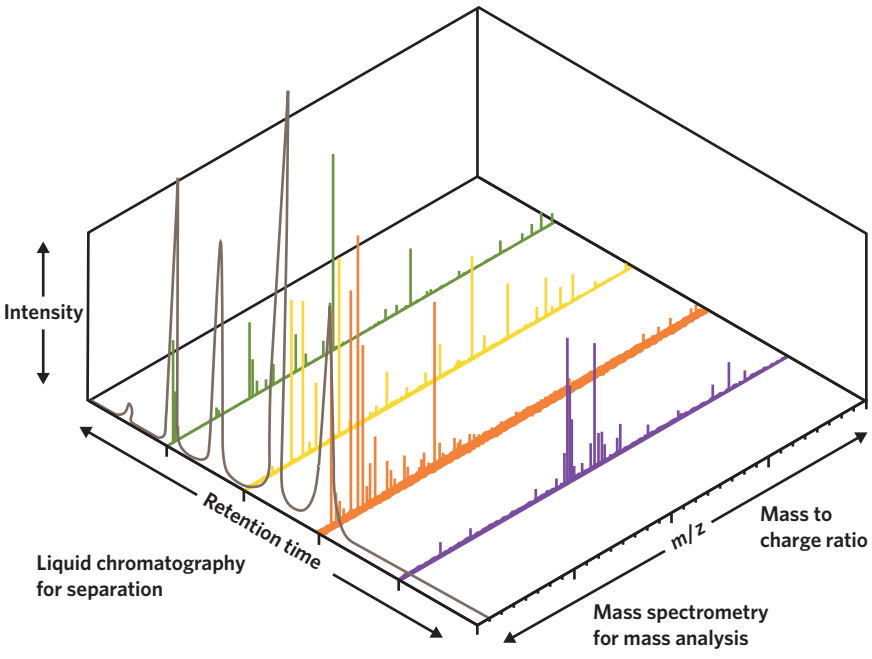


Figure 1 Combined chromatogram and mass spectrum from LC-MS analysis

Petrochemical applications

In the petrochemical industry, laboratory and instrumental analysis are used to assess the quality of crude oil in order to ensure compliance with regulatory standards.[1] For example, heavier petrochemical products can be analysed using LC-MS in a similar manner to its pharmaceutical application. However, gas chromatography – a chromatography technique in which gaseous substances pass through a column with a gaseous stationary phase – is utilised in the detection of impurities in petroleum products that are readily available in the gas phase.

KEEN TO INVESTIGATE?

[1] **How are analytical techniques used to make cleaner petrol?**
Search: How is Chromatography Used in Petroleum Refining? PIN

How can analysis techniques be used to determine the identity of organic compounds and functional groups in a sample?

Laboratory and instrumental analysis are key in determining the identity of organic compounds. A combination of the techniques explored in chapter 10 can be employed to deduce the functional groups in a compound, the mass of a compound, and the overall structure of the compound. The use of each technique in identifying organic compounds is outlined in table 3.

Table 3 Use of analytical techniques to identify organic compounds in a sample

Technique	Use in identifying organic compounds
Mass spectrometry	A mass spectrum provides information about the molar mass of a compound, and can help identify characteristic fragments formed in the ionisation phase that indicate the presence of specific functional groups.
Infrared (IR) spectroscopy	Different functional groups absorb infrared radiation at specific frequencies, or wave numbers, resulting in characteristic peaks in the IR spectrum. By analysing these characteristic peaks, the functional groups present in the sample can be identified.
Low resolution ^{13}C-NMR spectroscopy	A low resolution ^{13}C-NMR spectrum can be used to identify the number of non-equivalent carbon environments in a compound.
Low resolution ^{1}H-NMR spectroscopy	Like low resolution ^{13}C-NMR, low resolution ^{1}H-NMR may not provide detailed structural information, but it can indicate the presence of certain functional groups based on characteristic proton environments. Additionally, it can be used to identify the ratio of protons in the different proton environments.
High resolution ^{1}H-NMR spectroscopy	High resolution ^{1}H-NMR provides detailed structural information about organic compounds by revealing the specific arrangement of protons in a molecule through splitting patterns. This technique is highly effective in determining the connectivity of different functional groups within a compound and can help in the precise identification of organic molecules.
Chromatography	Gas chromatography and high performance liquid chromatography are commonly used in the identification of organic compounds. By comparing the retention times of unknown compounds with those of known standards, the organic compounds present in the sample can be identified.

Chemists will rarely use each of the techniques listed in table 3 in isolation. Instead, as with testing for purity, the results from several techniques will be combined to make precise inferences about the structure of and functional groups present in an organic compound. These techniques are frequently used in environmental analysis and forensic science.

Environmental analysis

Environmental chemists use laboratory and instrumental analysis to identify organic pollutants in soil, water, and air. For example, to assess the concentration of pollutants in the air, gas chromatography, mass spectrometry, and infrared spectroscopy are used. These methods can detect and quantify pollutants such as particulate matter, volatile organic compounds (VOCs), nitrogen oxides, sulfur dioxide, and carbon monoxide. This combination of techniques has been used for decades; figure 2 shows infrared spectra from a 1997 journal article containing research on VOCs present in the air of three South African cities.

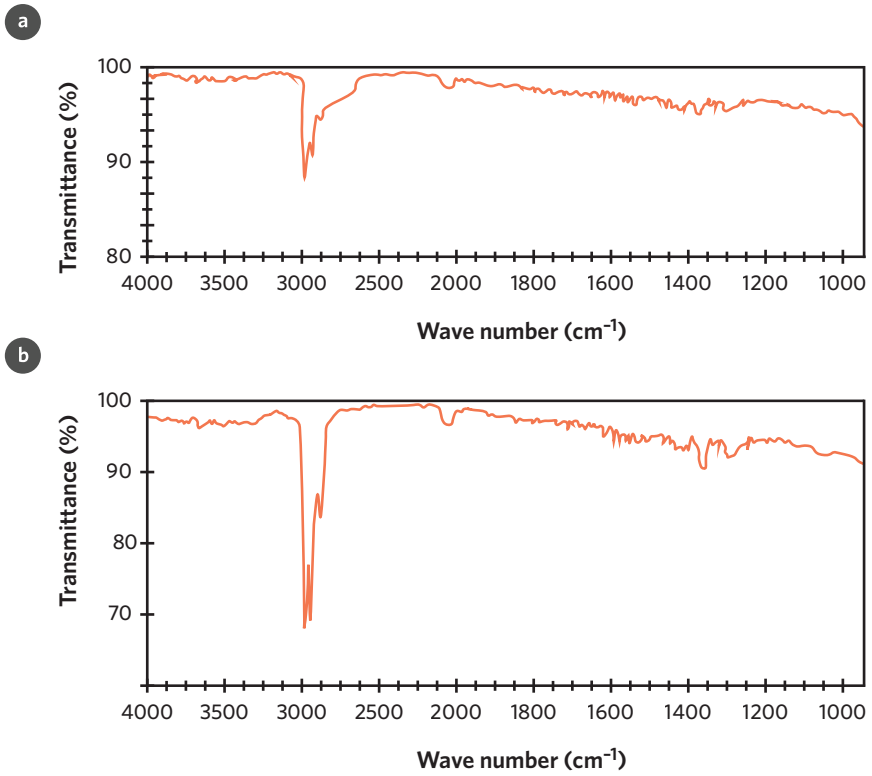


Figure 2 **(a)** Infrared spectrum of an unknown compound found in city air and **(b)** infrared spectrum of known VOC 3-methyloctane

Figure 2 demonstrates the identification of the volatile organic compound 3-methyloctane in the city air, as the infrared spectrum of the unknown compound is almost identical to the infrared spectrum of the sample of pure 3-methyloctane.

Forensic science

Laboratory and instrumental analysis are indispensable tools in forensic investigations. They help identify unknown substances found at crime scenes, such as drugs, toxic compounds, or unknown residues. ^{13}C-NMR and ^{1}H-NMR spectroscopy are utilised in time-of-death estimations as they can be used to identify the presence of certain compounds in the blood and tissue and use them to determine the rate of decomposition.

PROGRESS QUESTIONS

Question 2

Which instrumental technique is most suitable for determining the functional groups present in an organic compound?

A. ^{13}C-NMR spectroscopy

B. Chromatography

C. Infrared spectroscopy

D. Mass spectrometry

Theory summary

- Information provided by each instrumental analysis technique:

Technique	Information provided
Mass spectrometry	• Molar mass • Possible branching patterns
Infrared spectroscopy	• Functional groups present
^{13}C-NMR	• Number of non-equivalent carbon environments • Types of carbon environments present
^{1}H-NMR	• Number of non-equivalent proton environments • Ratio of protons in each environment • Types of proton environments present • Number of protons in neighbouring proton environments

- Laboratory and analysis techniques are often combined to gain more definitive information about the structure and identity of compounds.
- The purity of organic compounds in mixtures and in isolation can be qualitatively and quantitatively assessed using a combination of analytical techniques.
- The identity of organic compounds in mixtures and in isolation can be deduced using a combination of analytical techniques.

10F Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 3–5.

A compound has the molecular formula C_4H_9Cl.

Question 3 (1 MARK)

Which type of chemical analysis would be **most** useful in determining the number and ratio of protons in the compound?

A. Mass spectrometry
B. Infrared spectroscopy
C. High performance liquid chromatography
D. Nuclear magnetic resonance spectroscopy

Question 4 (1 MARK)

Which type of chemical analysis would be **most** useful in determining the types of bonds present in the compound?

A. Mass spectrometry
B. Infrared spectroscopy
C. High performance liquid chromatography
D. Nuclear magnetic resonance spectroscopy

Question 5 (1 MARK)

Which type of chemical analysis would be **most** useful in determining the structure of the compound?

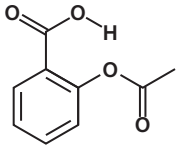
A. Mass spectrometry
B. Infrared spectroscopy
C. High performance liquid chromatography
D. Nuclear magnetic resonance spectroscopy

Adapted from VCAA 2019 exam Multiple choice Q12

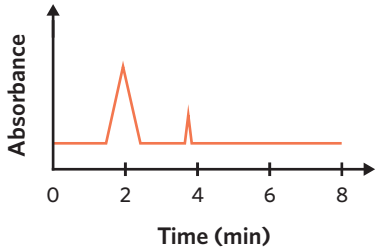
Exam-style

Question 6 (5 MARKS)

Loren is a chemist working for a pharmaceutical company. She is in charge of quality control at her laboratory, meaning her main task is to identify any impurities in the active ingredients produced at the laboratory before they are used in medications. She analyses a batch of aspirin, the structure of which is shown.



As part of her analysis, she runs some of the sample through high performance liquid chromatography and mass spectrometry at SLC. The resulting chromatogram is shown.



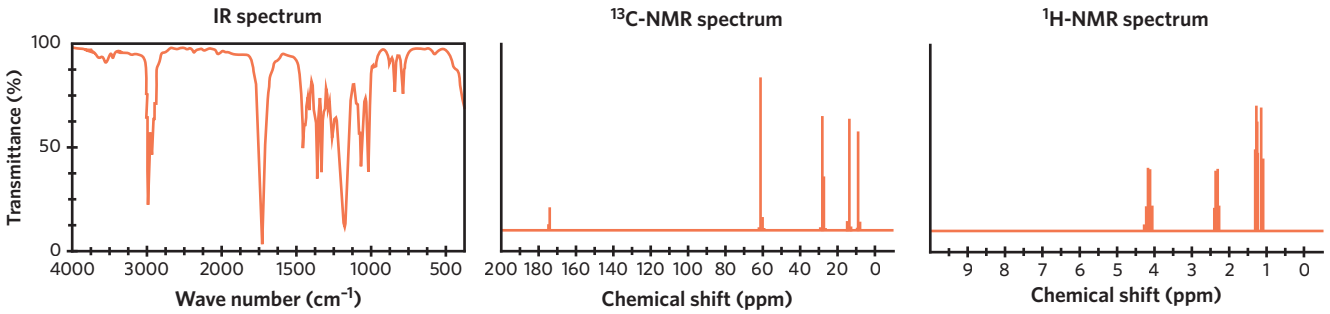
The standard retention time of pure aspirin under SLC is 2 minutes.

a. According to the chromatogram, does the batch being analysed contain 100% aspirin? Explain. 1 MARK

b. Loren determines that the batch contains an additional unknown organic compound. Once the unknown compound is separated from the aspirin sample, which two analysis techniques, aside from HPLC and mass spectrometry, could be used to determine the structure and identity of the additional unknown organic compound? Justify your answer. 4 MARKS

Question 7 (6 MARKS)

A compound has the molecular formula $C_5H_{10}O_2$. It is analysed by infrared (IR), ^{13}C-NMR, and ^{1}H-NMR spectroscopy. The resulting spectra are shown.



Information for the splitting pattern of the ^{1}H-NMR spectrum is given in the following table.

Chemical shift (ppm)	Relative peak area	Splitting pattern
4.1	2	4 peaks
2.3	2	4 peaks
1.3	3	3 peaks
1.1	3	3 peaks

a. Using the IR spectrum provided, identify a bond in a molecule of $C_5H_{10}O_2$ and give its wave number. 1 MARK

b. Using the ^{1}H-NMR spectrum provided, state the number of proton environments in a molecule of $C_5H_{10}O_2$. 1 MARK

c. What specific information about the structure of a molecule of $C_5H_{10}O_2$ is provided by the splitting pattern in the ^{1}H-NMR spectrum? 1 MARK

d. Draw a structure consistent with the data provided for a molecule of $C_5H_{10}O_2$. 2 MARKS

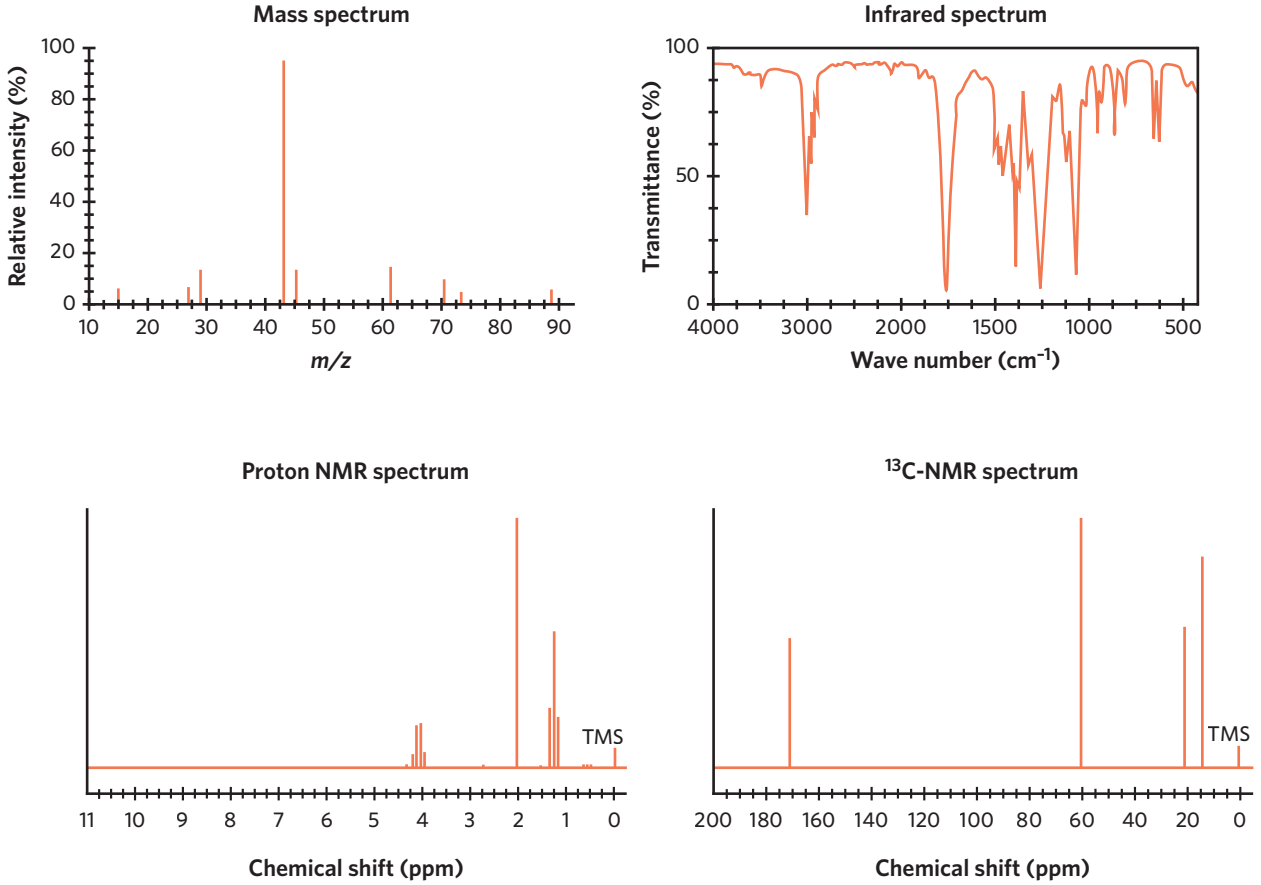
e. Explain how the structure you have drawn in part **d** is supported by evidence from the ^{13}C-NMR spectrum. 1 MARK

Adapted from VCAA (NHT) 2017 exam Short answer Q3

Key science skills

Question 8 (7 MARKS)

An unknown organic compound with the molecular formula $C_4H_8O_2$ was presented to a spectroscopy laboratory for identification. A mass spectrum, infrared spectrum, and both ^{1}H-NMR (proton NMR) and ^{13}C-NMR spectra were produced.



Using the spectra, the analytical chemist identified the compound as ethyl ethanoate. A report was submitted to justify the interpretation of the spectra. The chemist's report indicating information about the structure provided by the ^{13}C-NMR spectrum has been completed for you.

a. Complete the rest of the report by identifying one piece of information from each spectrum that can be used to identify the compound. Indicate how the interpretation of this information justifies the chemist's analysis. 6 MARKS

Spectroscopic technique	Information provided
^{13}C-NMR spectrum	The four signals in the ^{13}C-NMR spectrum indicate four different carbon environments. $CH_3COOCH_2CH_3$ has four different carbon environments.
Mass spectrum	
Infrared spectrum	
^{1}H-NMR spectrum	

b. Another compound has the same molecular formula as ethyl ethanoate. However, the carbon ^{13}C-NMR spectrum of this compound shows only three signals. Draw a possible structure of this compound. 1 MARK

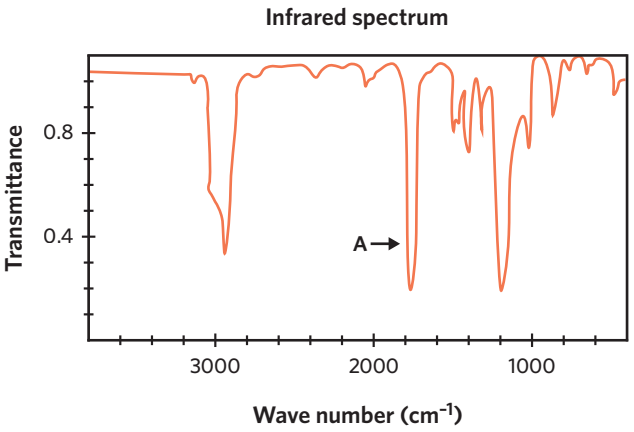
VCAA 2013 exam Short answer Q9

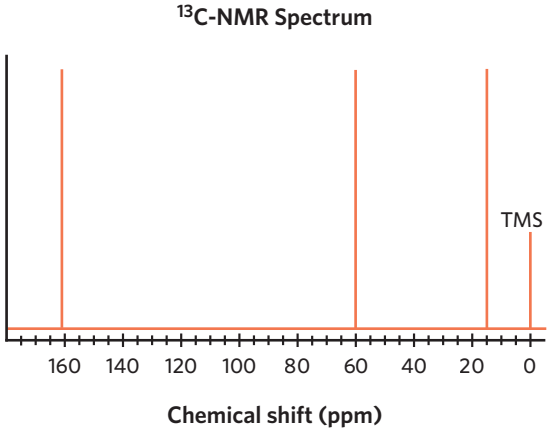
FROM LESSON 12C

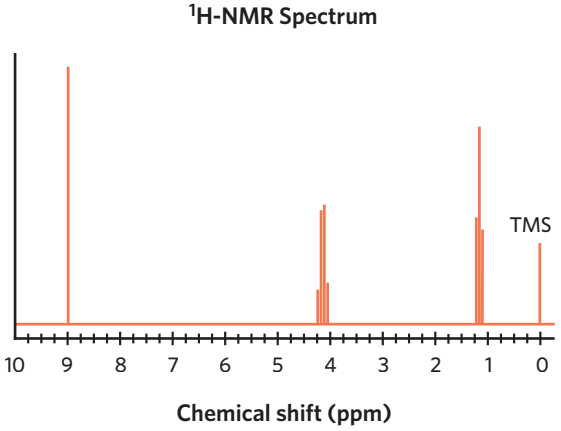
Questions from multiple lessons

Question 9 🌶🌶🌶 (7 MARKS)

The molecular formula of an unknown compound, X, is $C_3H_6O_2$. The infrared, ^{13}C-NMR and ^{1}H-NMR spectra of this compound are shown.







a. Identify the atoms and the bonds between them that are associated with the absorption peak labelled A on the infrared spectrum. 1 MARK

b. How many different carbon environments are present in compound X? 1 MARK

c. How many different proton environments are present in compound X? 1 MARK

d. The ^{1}H-NMR spectrum data is summarised in the following table.

Chemical shift (ppm)	Relative peak area	Peak splitting
1.3	3	Triplet
4.2	2	Quartet
9.0	1	Singlet

i. The signal at 1.3 ppm is split into a triplet. What is the number of equivalent protons bonded to the adjacent carbon atom? 1 MARK

ii. Draw the grouping of atoms that would give rise to the triplet and quartet splitting patterns. 1 MARK

e. A chemical test showed that compound X does **not** react with a base. Propose a structure for compound X that is consistent with all the evidence provided. 2 MARKS

VCAA 2010 Exam 1 Short answer Q2

FROM LESSONS 7A, 8A, 10B, 10C & 10D

Chapter 10 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

When a sample absorbs infrared radiation,

A. covalent bonds are broken.
B. covalent bonds stretch and vibrate to a greater extent.
C. the spin alignment of certain nuclei changes.
D. electrons in atoms move to higher energy levels.

Adapted from VCAA 2010 Exam 1 Multiple choice Q8

Question 2 (1 MARK)

Which of the following would be the most suitable analytical technique to determine the ratio of ^{235}U to ^{238}U in a sample of uranium metal?

A. Mass spectroscopy
B. Infrared spectroscopy
C. High performance liquid chromatography
D. Nuclear magnetic resonance spectroscopy

Adapted from VCAA 2010 Exam 1 Multiple choice Q7

Question 3 (1 MARK)

Which one of the following techniques is most suitable for distinguishing between 1,1,1-trichloropropane and 1,2,3-trichloropropane?

A. Infrared spectroscopy
B. High resolution ^{1}H-NMR spectroscopy
C. Mass spectrometry
D. Chromatography

Adapted from VCAA 2015 exam Multiple choice Q12

Question 4 (1 MARK)

The molecular ion of a compound analysed using mass spectrometry has the symbol $[D]^+$. Some of the molecular ions fragment according to the following equations.

$[D]^+ \rightarrow [X]^+ + Y$

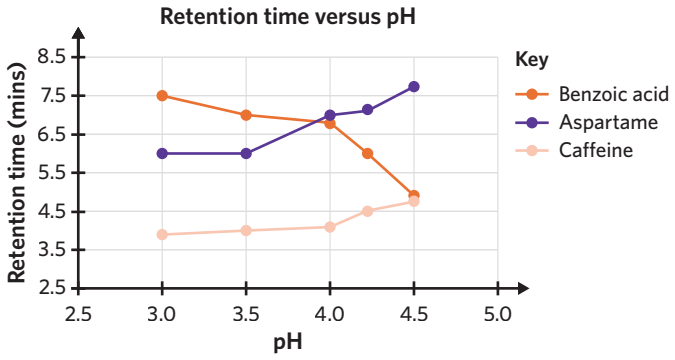
$[D]^+ \rightarrow X + [Y]^+$

The resulting mass spectrum would show peaks due to

A. D and $[D]^+$.
B. D, X, and Y.
C. $[D]^+$, $[X]^+$, and $[Y]^+$.
D. $[X]^+$ and $[Y]^+$.

Use the following information to answer questions 5–6.

A student is designing an experiment to determine the concentration of aspartame in soft drinks using high performance liquid chromatography (HPLC). Aspartame, benzoic acid and caffeine are all common components of soft drinks. Under some conditions, they have similar retention times in an HPLC column. The graph provided shows the retention times for these substances at different pH values.



Question 5 (1 MARK)

According to the graph, which pH value would provide the largest separation of aspartame, benzoic acid, and caffeine?

A. 3.0 **B.** 4.0 **C.** 4.3 **D.** 4.5

VCAA (NHT) 2019 exam Multiple choice Q8

Question 6 (1 MARK)

Which one of the following would minimise sources of error and uncertainty in the student's experiment?

A. Dilute the samples of soft drinks prior to analysis by HPLC.

B. Use a different mobile phase for each type of soft drink investigated.

C. Analyse three aliquots of each sample of soft drink through the HPLC instrument.

D. Increase the pH of the samples of soft drinks by adding hydrochloric acid.

VCAA (NHT) 2019 exam Multiple choice Q9

Question 7 (1 MARK)

Petrol is a mixture of hydrocarbon molecules varying in size from six to ten carbon atoms. Forensic investigators suspect that traces of a substance found at a suspicious fire could be petrol that was used to start the fire. Which one of the following techniques would be best used to identify the substance?

A. NMR spectroscopy

B. Infrared spectroscopy

C. High performance liquid chromatography

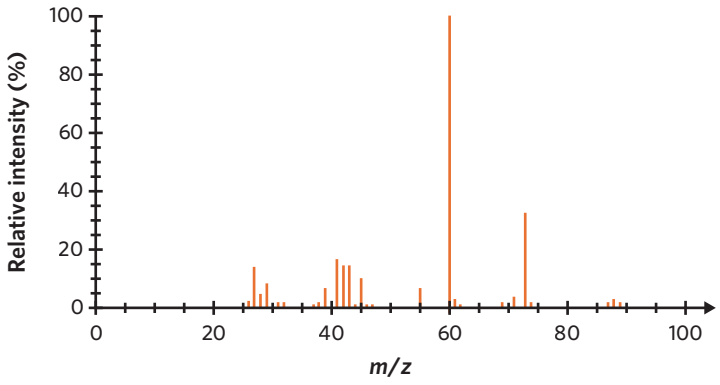
D. Gas chromatography followed by mass spectroscopy

Adapted from VCAA 2011 Exam 1 Multiple choice Q12

Question 8 (1 MARK)

An unidentified organic substance with the molecular formula $C_4H_8O_2$ is found to react with a base. Mass spectrometry shows the parent molecular ion has a mass-to-charge ratio, m/z, of 88.

Which one of the following species is consistent with a peak on the mass spectrum at $m/z = 45$?



A. $[COOH]^+$

B. $[CH_3CH_2O]^+$

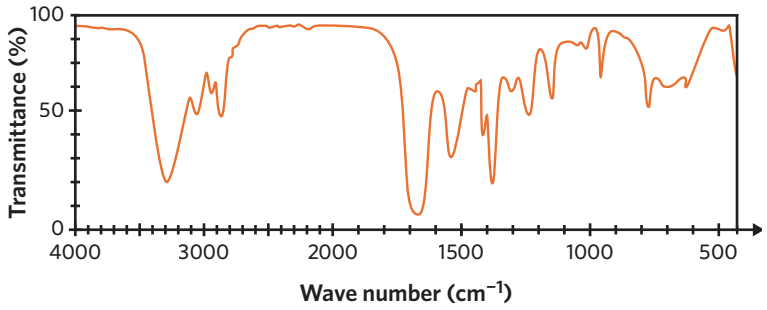
C. $[CH_3CH_2OH]^+$

D. $[CH_3CH_2CH_2COOH]^+$

VCAA (NHT) 2017 exam Multiple choice Q8

Question 9 (1 MARK)

Shown below is the infrared spectrum of an organic compound.



The compound consistent with the infrared spectrum is

A. ethanal. **B.** 2-propanol. **C.** butan-1-amine. **D.** octanamide.

Adapted from VCAA 2017 exam Multiple choice Q17

Question 10 (1 MARK)

A high-performance liquid chromatography (HPLC) column has a non-polar stationary phase and a polar solvent as the mobile phase. Which one of the following substances would have the lowest retention time?

A. Tetrachloromethane **B.** Chloromethane **C.** Bromomethane **D.** Hexane

VCAA (NHT) 2021 exam Multiple choice Q27

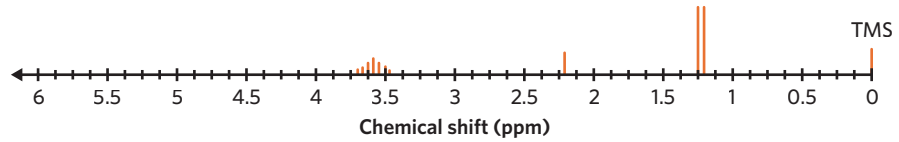
Short answer (30 MARKS)

Question 11 (5 MARKS)

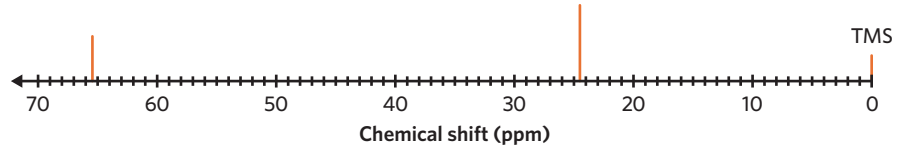
An organic chemist found a bottle in the laboratory that was labelled 'organic cleaning fluid, C_3H_8O'. She decided to test the liquid. The chemist obtained the following data about the compound in the cleaning fluid: the ^{1}H-NMR and ^{13}C-NMR spectra, and the infrared spectrum. The ^{1}H-NMR data is summarised in the table provided.

Chemical shift (ppm)	Relative peak area	Peak splitting
1.2	6	Doublet (2)
2.2	1	Singlet (1)
3.6	1	Septet (7)

^{1}H-NMR spectrum



^{13}C-NMR spectrum



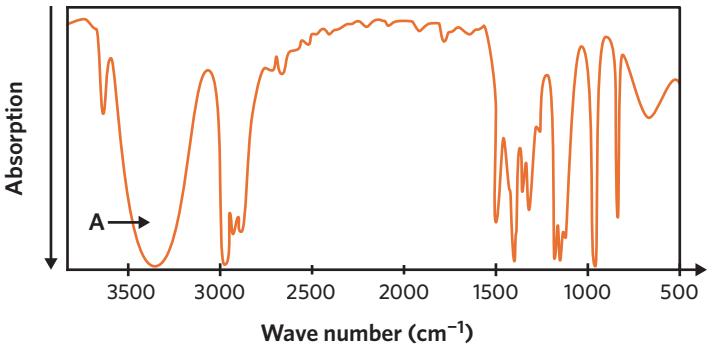
a. Consider the NMR spectra shown.

i. How many different carbon environments are present in the compound? 1 MARK

ii. How many different hydrogen environments are present in the compound? 1 MARK

iii. In the ^{1}H-NMR spectrum, the signal at 3.6 ppm is split into a septet.
What is the number of equivalent protons that are bonded to the adjacent carbon atom(s)? 1 MARK

b. The infrared spectrum obtained is shown.



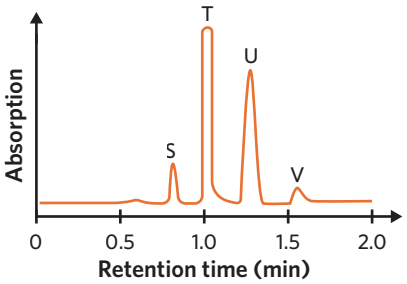
Identify the atoms that are associated with the absorption peak labelled A on the infrared spectrum. 1 MARK

c. Draw a structure of the compound in the cleaning fluid that is consistent with the NMR and IR data. 1 MARK

VCAA 2012 Exam 1 Short answer Q5

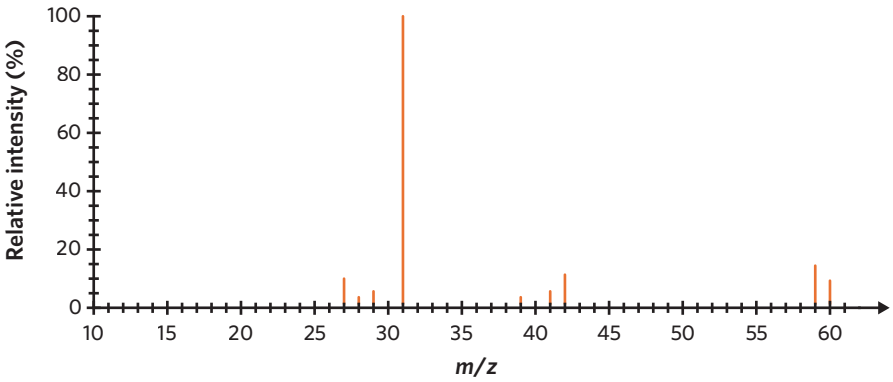
Question 12 (6 MARKS)

A mixture containing four straight chain alcohols, S, T, U, and V, each with a general formula ROH, was analysed using a gas chromatograph combined with a mass spectrometer. The following chromatogram and peak area data were produced.



Alcohol	S	T	U	V
Peak area (mm^2)	900	5000	3900	40

The mass spectrum of alcohol T is shown.



a. What is the order of the alcohols from highest molar mass to lowest molar mass? 1 MARK

b. Which of the alcohols is present in the highest concentration? 1 MARK

c. Alcohol T is a primary alcohol. Draw the structural formula of alcohol T. 1 MARK

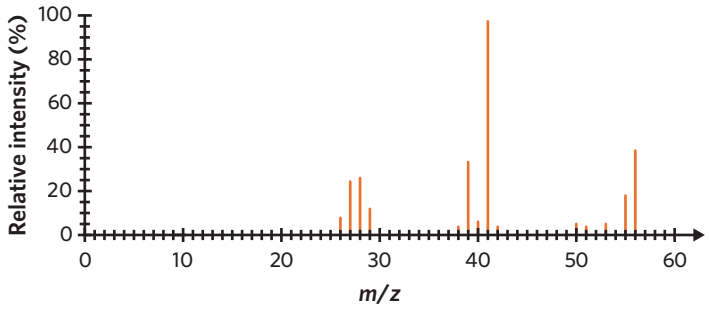
d. Identify the molecular formula for a fragment ion that could be responsible for the base peak. 1 MARK

e. Explain how gas chromatography and mass spectrometry can be combined to identify the molar mass of each alcohol present in the mixture. 2 MARKS

Adapted from VCAA 2014 exam Multiple choice Q12,13

Question 13 (10 MARKS)

A chemist has a sample of an unknown hydrocarbon, Molecule L. The mass spectrum of Molecule L is shown.



a. Consider the mass spectrum of Molecule L.

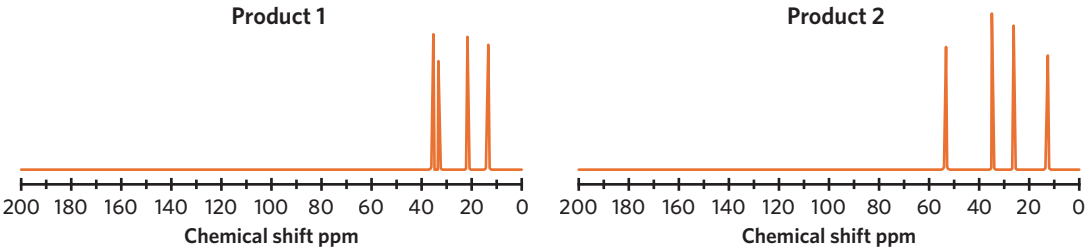
i. What is the m/z of the base peak? 1 MARK

ii. What is the molecular formula of Molecule L? 1 MARK

iii. Identify the fragment that produces the peak at 41 m/z. 1 MARK

b. Draw the structural formulas for two isomers of Molecule L. 2 MARKS

c. The chemist finds that Molecule L reacts with hydrogen bromide, HBr, to form two products that are isomers. The ^{13}C-NMR spectra of the two products are shown below.



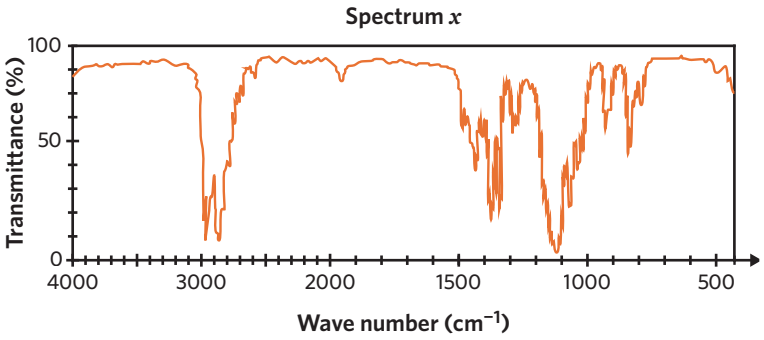
i. Write the semi-structural formula of Molecule L. 1 MARK

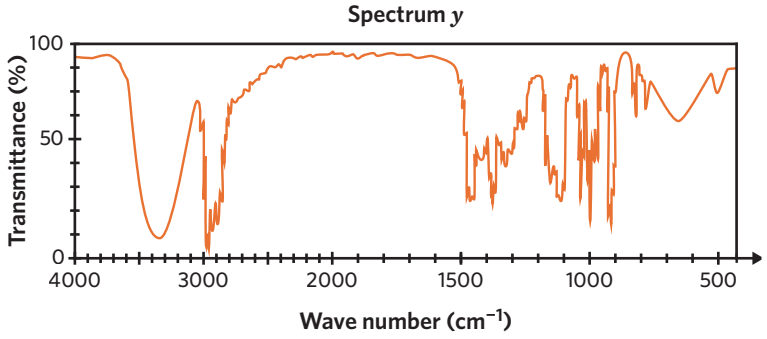
ii. The information from the ^{1}H-NMR spectrum of Product 1 is shown in the table.

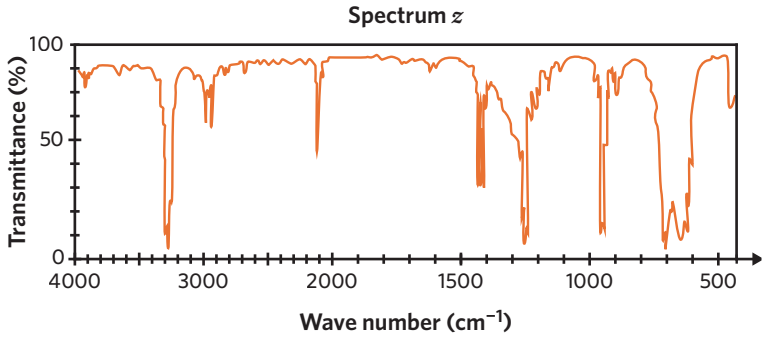
Chemical shift (ppm)	3.4	1.8	1.5	0.9
Relative peak area	2	2	2	3

Use this information to give the IUPAC systematic name for product 1. 1 MARK

d. Molecule L undergoes a hydration reaction. Spectrum x, Spectrum y, and Spectrum z are the spectra for three different compounds.





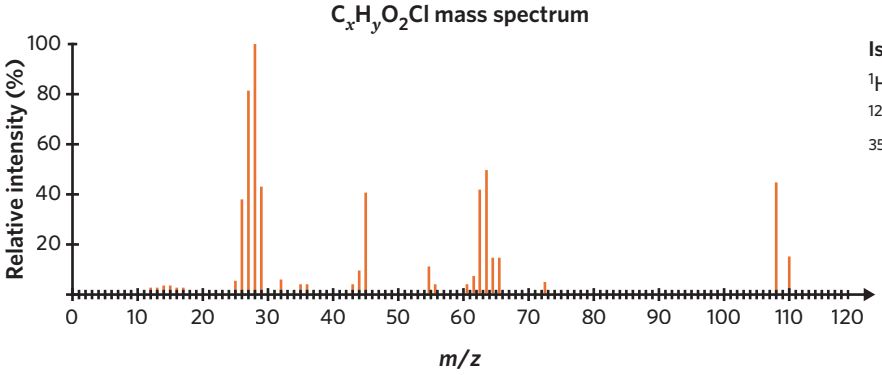


Which of the spectra shown is consistent with a product of the hydration reaction for Molecule L? Your answer should make reference to the information in the spectra. 3 MARKS

VCAA (NHT) 2021 exam Short answer Q8

Question 14 (9 MARKS)

A small organic molecule has the molecular formula of the form $C_xH_yO_2Cl$. A pH probe was inserted into a dilute aqueous solution of this compound, and the pH was 4.5. The mass spectrum, infrared spectrum, ^{13}C-NMR spectrum, and low resolution ^{1}H-NMR spectrum of this compound are provided.

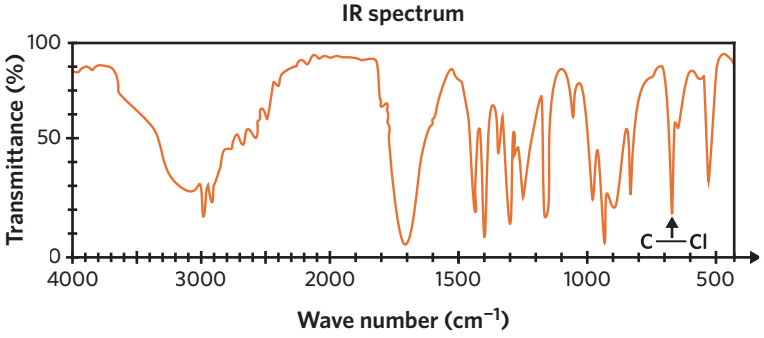


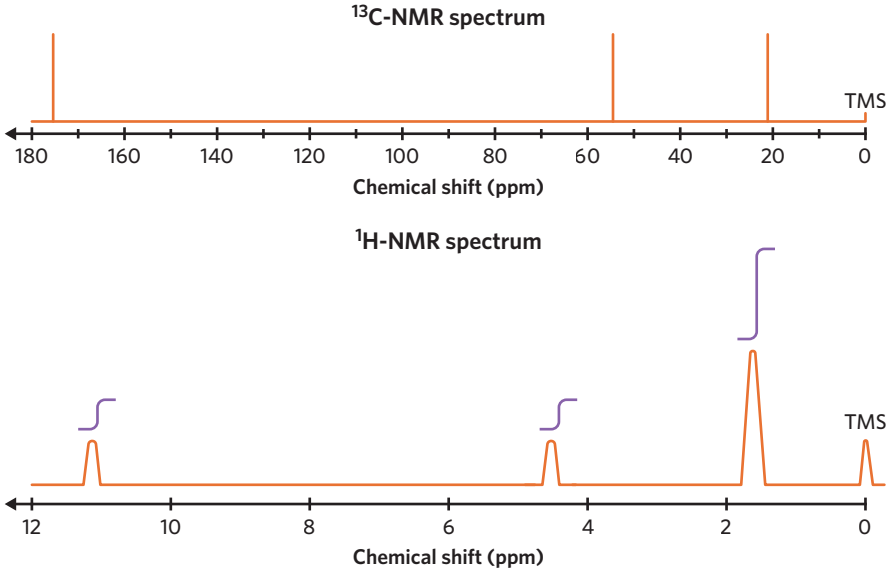
Isotope data

$^{1}H : {}^{2}H$ = 99.99 : 0.01

$^{12}C : {}^{13}C$ = 98.93 : 1.07

$^{35}Cl : {}^{37}Cl$ = 75.78 : 24.22





a. Identify two peaks on the infrared spectrum that correspond to the presence of functional groups in this compound. Note: The peak due to the C—Cl stretch has already been labelled. 2 MARKS

b. Use the data provided to determine the values of x and y in $C_xH_yO_2Cl$. 2 MARKS

c. The splitting patterns shown on the high resolution ^{1}H-NMR spectrum of the compound are given in the following table.

Chemical shift (ppm)	1.7	4.5	11.2
Peak splitting	Doublet	Quartet	Singlet

i. What specific information about the structure of the compound is provided by the integration curves on the low resolution ^{1}H-NMR spectrum? 1 MARK

ii. What specific information about the structure of the compound is provided by the splitting patterns in the high resolution ^{1}H-NMR spectrum? 1 MARK

iii. Draw the structural formula for this molecule. 1 MARK

d. Give a reason why the mass spectrum shows two molecular ion peaks, one at $m/z = 108$ and one at $m/z = 110$, rather than just one. In your answer, give the semi-structural formulas for the compounds responsible for each molecular ion peak. 2 MARKS

Adapted from VCAA 2014 exam Short answer Q4

Key science skills (10 MARKS)

Question 15 (7 MARKS)

Caffeine is a stimulant drug that is found in coffee, tea, energy drinks, and some soft drinks. The concentration of caffeine in drinks can be determined using high performance liquid chromatography (HPLC). The retention time of caffeine is 96 seconds.

Four caffeine standard solutions containing 50 ppm, 100 ppm, 150 ppm, and 200 ppm of caffeine were prepared. 25 µL of each sample was injected into the HPLC column. The peak areas for each standard solution are given in the following table.

Concentration of caffeine standard solution (ppm)	50	100	150	200
Peak area	4000	9400	14 100	18 700

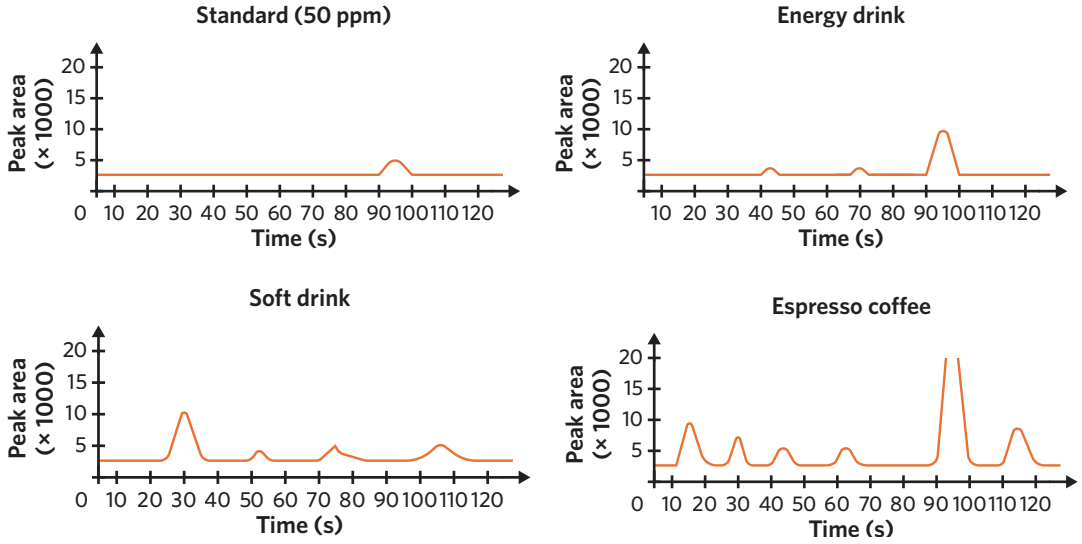
a. Construct a calibration curve for the caffeine standard solutions. 3 MARKS

b. 25 µL samples of three drinks thought to contain caffeine were then separately passed through the HPLC column. The results are summarised in the table provided.

Sample	Retention time of major peak (seconds)	Peak area of largest peak
Energy drink	96	12 000
Soft drink	32	8500
Espresso coffee	96	211 000

Use your calibration curve from part **a** to determine the concentration of caffeine, in ppm, in the energy drink. 1 MARK

c. The chromatograms of each drink are given.



i. According to the chromatogram, does the soft drink contain caffeine? Explain. 1 MARK

ii. Explain why the caffeine content of the espresso coffee sample cannot be reliably determined using the information provided. 1 MARK

iii. Describe what could be done to the espresso coffee sample so that its caffeine content can be determined using the information provided. 1 MARK

Adapted from VCAA 2011 Exam 1 Short answer Q3

FROM LESSONS 12B, 12C & 12E

Question 16 🌶🌶🌶 (3 MARKS)

The composition of fatty acids found in an egg yolk sample is given in the following table.

Fatty acid	Percentage (%)
Palmitic	25.9
Stearic	9.1
Palmitoleic	3.4
Oleic	40.9
Linoleic	16.3
Linolenic	2.9
Arachidonic	1.5

The composition of fatty acids in an egg yolk was determined by reacting the fatty acids with methanol to produce methyl esters and then analysing the methyl esters using chromatography. Explain, using the principles of chromatography, how each fatty acid in the egg yolk sample can be identified and the percentage determined.

Adapted from VCAA 2020 exam Short answer Q7bi

FROM LESSONS 12B & 12E

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11

CHAPTER 11
Medicinal chemistry

LESSONS

11A Extraction, purification and identification of medicinal molecules

11B Enzymes and medicines

Chapter 11 review

KEY KNOWLEDGE

- extraction and purification of natural plant compounds as possible active ingredients for medicines, using solvent extraction and distillation
- identification of the structure and functional groups of organic molecules that are medicines
- significance of isomers and the identification of chiral centres (carbon atom surrounded by four different groups) in the effectiveness of medicines
- enzymes as protein-based catalysts in living systems: primary, secondary, tertiary and quaternary structures and changes in enzyme function in terms of structure and bonding as a result of increased temperature (denaturation), decreased temperature (lowered activity), or changes in pH (formation of zwitterions and denaturation)
- medicines that function as competitive enzyme inhibitors: organic molecules that bind through lock-and-key mechanism to an active site preventing binding of the actual substrate

Image: New Africa/Shutterstock.com

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11A Extraction, purification and identification of medicinal molecules

STUDY DESIGN DOT POINTS

- extraction and purification of natural plant compounds as possible active ingredients for medicines, using solvent extraction and distillation
- identification of the structure and functional groups of organic molecules that are medicines
- significance of isomers and the identification of chiral centres (carbon atom surrounded by four different groups) in the effectiveness of medicines

11A 11B

- 4.2.12.1 Solvent extraction and distillation of natural plant compounds
- 4.2.13.1 Medicinal organic molecules
- 4.2.14.1 Chirality

ESSENTIAL PRIOR KNOWLEDGE

- Polarity
- Partial charges

7A Benzene
7A Isomers
10F Instrumental techniques

See questions 88-92.


Image: lv-olga/shutterstock.com

How can oil from this tree fight infection?

The tea tree is a plant native to Australia that has been used as a medicine by Aboriginal and Torres Strait Islander Peoples for thousands of years. In this lesson, we will investigate how **medicinal molecules** are extracted from plants and subsequently purified, exploring some important plant-sourced medicines from Australia and around the world. The significance of structure, functional groups, and chirality to medicinal molecules will also be explored.

KEY TERMS AND DEFINITIONS

Achiral compound compound with a superimposable mirror image
Active ingredient component of a substance or mixture that produces a chemical or biological effect
Chiral centre carbon atom in a compound attached to four unique chemical environments
Chiral compound compound with a non-superimposable mirror image
Immiscible describes a set of liquids that do not mix with each other
Medicinal molecule compound with healing properties
Optical isomers two non-superimposable mirror images of the same compound
Racemate an approximately 50/50 mixture of a chiral compound's two optical isomers, which does not rotate polarised light in a specific direction
Simple distillation technique used to separate liquids with significantly different boiling points
Solvent extraction method of separating compounds based on a difference in solubility in two solvents
Steam distillation distillation by injection of water vapour to lower the boiling point of substances and hence minimise decomposition

Solvent extraction and distillation of natural plant compounds 4.2.12.1

For thousands of years, humans have used plants as a source of medicinal compounds. Various laboratory techniques can be employed to extract and purify these compounds for analysis and subsequent medicinal use.

USEFUL TIP

In representations of larger molecules, thick triangle-shaped lines ('wedges') are often used to represent bonds 'coming out of the page', whereas striped triangle-shaped lines ('dashes') are used to represent bonds 'going into the page'. These are used to show the molecule's 3D shape on a 2D page.

What medicinal molecules are extracted from plants?

Tea tree oil

Tea tree oil is a mixture extracted from the tea tree (*Melaleuca alternifolia*), which is native to Australia. Aboriginal and Torres Strait Islander Peoples have traditionally used tea tree oil as a medicine for treating insect bites and superficial wounds. The major component and possible **active ingredient** in tea tree oil is terpinen-4-ol (figure 1).

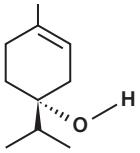


Figure 1 Structure of terpinen-4-ol, a major component of tea tree oil

Emu bush extract

Eremophila alternifolia is a species of emu bush (figure 2), another plant native to Australia which grows primarily in south-western Australia. Its leaves have been dried and used by Aboriginal and Torres Strait Islander Peoples to treat septic wounds, among other ailments associated with infection. As will be explored later in this lesson, modern analytical techniques have been applied to determine and isolate the potential active ingredients in this plant.



Image: alybaba/shutterstock.com

Figure 2 Emu bush

Paclitaxel

Paclitaxel, commonly sold as Taxol© (figure 3) is listed as an essential medicine by the World Health Organisation for its effectiveness in treating breast cancer, ovarian cancer, lung cancer, and others. Notably, it is almost exclusively obtained by extraction from the Pacific Yew Tree (*Taxus brevifolia*), which is native to North America.

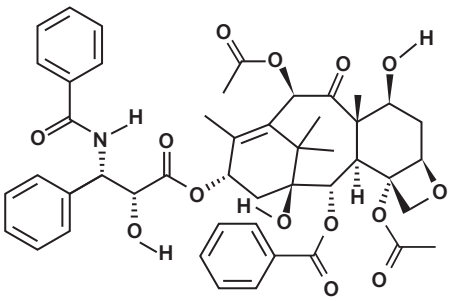


Figure 3 Structure of paclitaxel

Paclitaxel's success initially led to concerns surrounding the sustainability of yew forests, since extraction from the bark kills the tree. However, scientists have since developed methods of extracting a reactive compound that can be made into paclitaxel from the needles of Pacific and European yew trees (figure 4), hence keeping the tree alive.



Image: OlgaLo/shutterstock.com

Figure 4 Pacific yew tree needles

How are medicinal molecules extracted from plants?

As discussed in lesson 10E, 'like dissolves like': polar solvents dissolve polar solutes, whereas non-polar solvents dissolve non-polar solutes. This principle can be employed to separate desired compounds from impurities based on differences in polarity, in a process called **solvent extraction** or liquid-liquid extraction.

In this process, the initial mixture, containing the product we wish to extract and some impurities, is dissolved in a given solvent. Another solvent **immiscible** with the first is then added to the system, and the vessel is agitated (shaken). As a result, the two immiscible solvents come in contact with each other, and any solutes that are more soluble in the new solvent (compared with in the initial one) will partition (transfer) to the new solvent. Table 1 shows some common solvents used in solvent extraction.

USEFUL TIP

Polarity is largely relative, meaning compounds are best described as more or less polar than other compounds, rather than 'absolutely polar' or 'absolutely non-polar'.

Table 1 Common solvents and their polarities

Solvent	Polarity
Hexane	Very non-polar
Acetone (propanone)	Quite non-polar
DMSO (dimethylsulfoxide)	Somewhat polar, somewhat non-polar
Ethanol	Quite polar
Water	Quite polar

Figure 5 represents an example of solvent extraction. In this example, a mixture containing a desired product that is less polar and impurities that are more polar is initially dissolved in a non-polar solvent (e.g. hexane). A polar solvent (e.g. water) is added, and upon shaking, the polar impurities dissolve in this polar solvent, whilst the less polar desired product remains in the non-polar solvent. Since the two solvents are immiscible, they are then separated by opening the separating funnel tap, and the desired product can then be extracted via evaporation of the solvent.

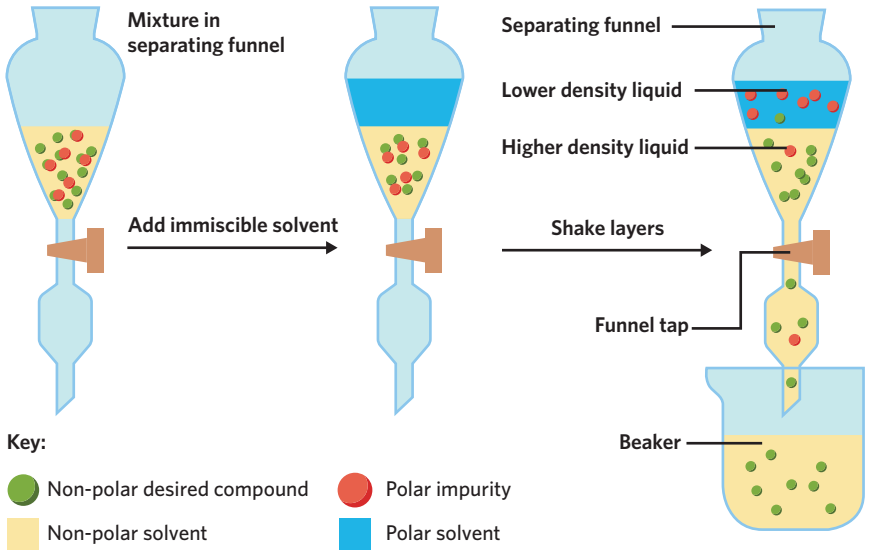


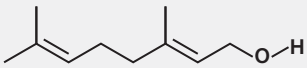
Figure 5 Example of solvent extraction

One of the primary uses of solvent extraction is to isolate oils from mixtures. Since oils contain long hydrocarbon chains and are hence largely non-polar, they dissolve well in non-polar solvents, and so can be separated from more polar impurities. To determine the optimal solvents to use for extraction, it is necessary to be able to identify the polar and non-polar regions of a molecule, and hence its overall polarity.

However, solvent extraction has its limitations. The process can be slow, and requires large volumes of solvents at an industrial scale. Solvent extraction is also ineffective at removing impurities with a similar polarity to the desired compound as they will likely dissolve to a similar extent in a given solvent, preventing them from being separated.

WORKED EXAMPLE 1

A cosmetics brand is looking to use solvent extraction to extract the compound geraniol (shown below) from roses. Would geraniol dissolve better in a more polar or non-polar solvent?



What information is presented in the question?

The structural formula of geraniol.

What is the question asking us to do?

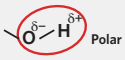
Determine whether geraniol would dissolve better in a polar or non-polar solvent.

What strategies do we need in order to answer the question?

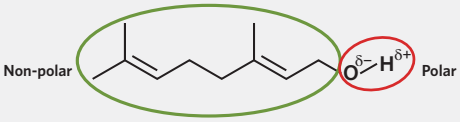
1. Identify any polar regions in the molecule.
2. Compare the relative size of the polar and non-polar regions of the molecule.
3. Assess the overall polarity of the molecule.

Answer

Since oxygen is significantly more electronegative than hydrogen, a polar bond exists between −O and −H in this compound. This forms a polar region around the hydroxyl group, shown in red.



The rest of the molecule consists only of carbon and hydrogen atoms (which have similar electronegativity), and so is considered non-polar, shown in green.



Since the polar (green) region appears much larger than the non-polar (red) region, geraniol is predominantly non-polar. Since 'like dissolves like', geraniol will hence likely dissolve better in a non-polar solvent than a polar solvent.

USEFUL TIP

Anti-bumping granules (also known as boiling chips) are added to the distillation mixture to distribute heat more evenly, producing smaller bubbles when the mixture boils and hence reducing the risk of explosion.

How are medicinal molecules purified after extraction?

As mentioned, the product of solvent extraction is often highly impure. To further purify this extract, a common method used is distillation, which involves the separation of liquids based on a difference in their boiling points.

Simple distillation can be used to separate two substances (usually liquids) with significantly different boiling points. This process, shown in figure 6, works by heating the mixture until the substance with the lower boiling point vaporises, transporting these vapours to a separate chamber, and then recondensing them, hence separating the two liquids. For example, simple distillation can be used to separate a mixture of water and ethanol, which is used to prevent skin infections. Since ethanol has a lower boiling point than water (78 °C vs. 100 °C), it can be vaporised at a lower temperature, separated from water, and recondensed. When heating fuels like ethanol, a heating mantle must be used (instead of a Bunsen burner) to minimise risk of explosion.

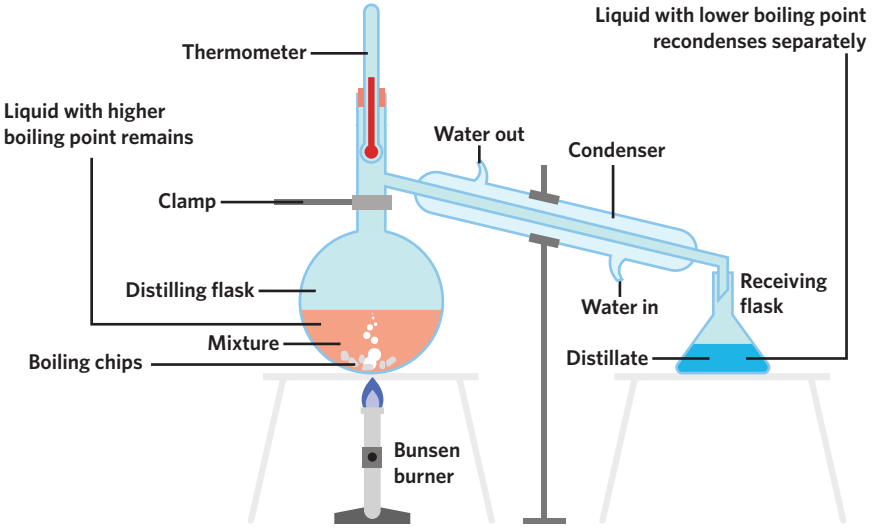


Figure 6 Simple distillation apparatus

However, some molecules are heat-sensitive, meaning that the high temperatures required for vaporisation can damage the structure of the molecule (a type of chemical decomposition). This is particularly true for compounds with high boiling points, such as oils, as simple distillation can alter their structure and hinder their medicinal properties.

As a result, a much more commonly used method for purifying compounds from plants is **steam distillation** (figure 7). In this process, water vapour:

- is pumped through the distillation apparatus
- reduces the temperature required to vaporise the substances in the mixture
- minimises decomposition of heat-sensitive compounds
- therefore preserves the desired product.

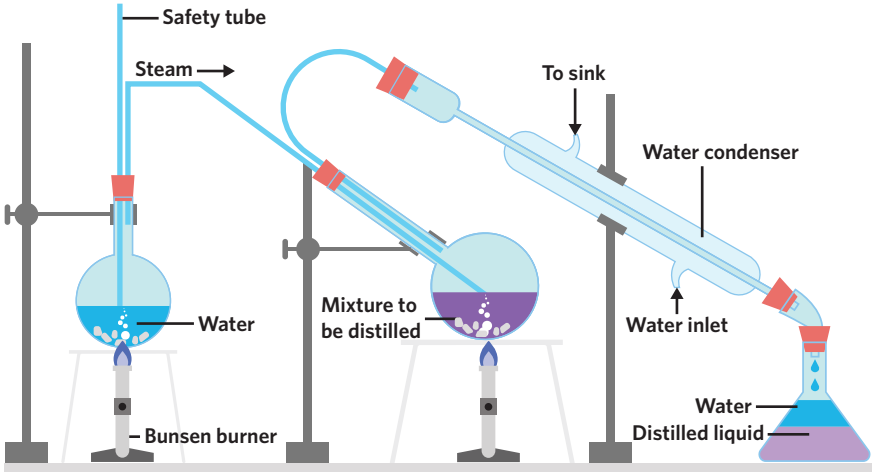


Figure 7 Steam distillation apparatus

Although boiling point is the lowest temperature at which a substance is present entirely in gaseous form, at lower temperatures, a portion of the substance is present as a gas. As a result of this, in the distillation process, a percentage of the substance with the higher boiling point will be vaporised and recondensed alongside the other, meaning that the product of distillation is never entirely pure. Accordingly, the distillation process is usually repeated many times to maximise the purity of the product, as outlined in figure 8

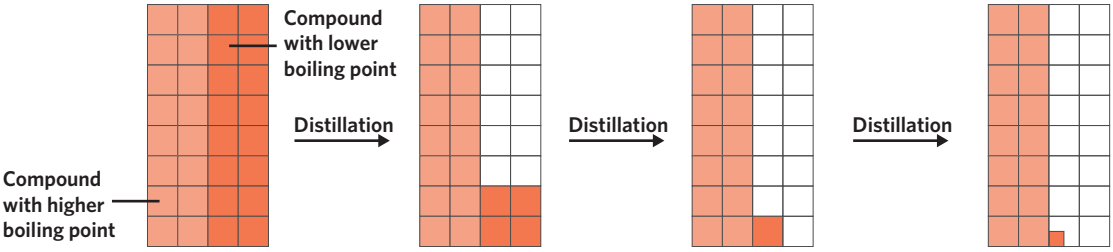


Figure 8 Representation of distillation, where three quarters of the remaining undesired compound is distilled at each stage

PROGRESS QUESTIONS

Question 1

An appropriate pair of solvents for use in solvent extraction is

A. heptane and hexane.

B. heptane and water.

C. water and methanol.

D. deionised water and seawater.

Question 2

Which is the most appropriate technique for separating hexane and octane?

A. Distillation

B. Decomposition

C. Solvent extraction

D. Isolation

Question 3

Why is steam distillation preferable to simple distillation for purifying oils?

A. Oils have high boiling points.

B. Oils are heat-sensitive.

C. Steam distillation prevents decomposition of oils.

D. All of the above

Medicinal organic molecules 4.2.13.1

A medicine is any substance that can be used to treat or cure an ailment. Many of the instrumental techniques studied in chapter 10 can be applied to medicines, enabling their structures and functional groups to be determined.

How can we identify medicinal molecules?

Whilst some medicines have been used and considered effective for thousands of years, it is only with the development of advanced analytical techniques that scientists have been able to determine the exact composition of active ingredients within medicines, and thus research exactly what makes these medicines effective. The analytical methods explored in chapter 10 can be employed for this.

This process can be explored through the case study of the emu bush, *Eremophila alternifolia*. Firstly, a mixture containing potential active ingredients is extracted from plants using solvent extraction (among other methods). Scientists predict potential compounds present in the mixture using chemical tests and prior knowledge. These potential compounds are then analysed using high-performance liquid chromatography (HPLC), and their respective chromatograms are compared to qualitatively determine which compounds are present in the mixture.

The chromatogram obtained for the emu bush extract is shown in figure 9.

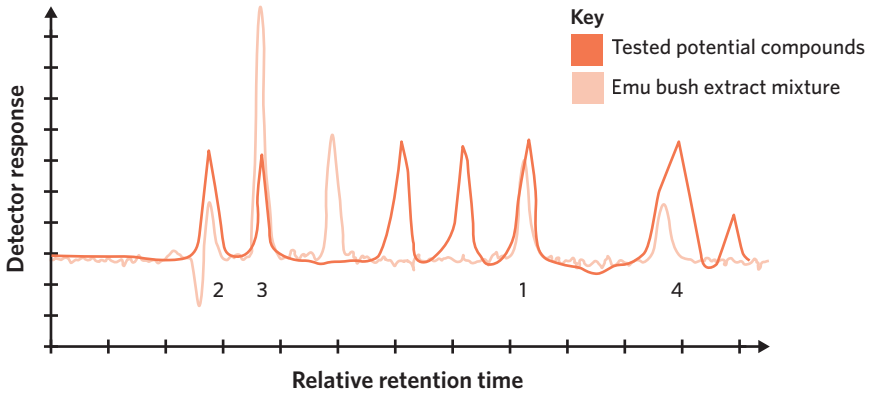


Figure 9 Sample HPLC chromatogram for emu bush extract and a number of potential compounds

Following this, the peak areas of the constituent compounds can be compared to quantitatively determine the relative percentage of each compound in the mixture. Finally, mass spectroscopy (MS), infrared spectroscopy (IR), and nuclear magnetic resonance spectroscopy (^{1}H-NMR and ^{13}C-NMR) are used to determine the functional groups and exact structures of the compounds present. Figure 10 displays the structures of each investigated potential active ingredient present in the emu bush extract.

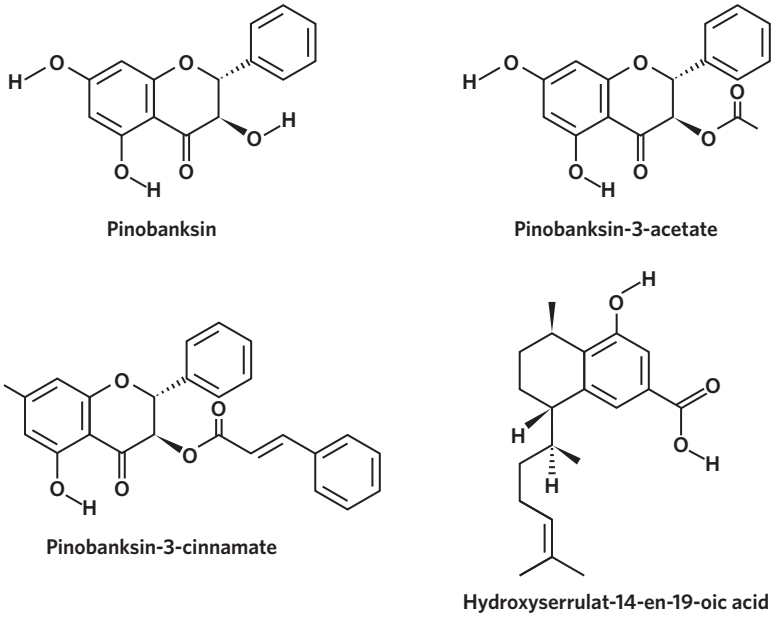


Figure 10 Structures of potential active ingredients in emu bush extract

As will be further discussed in lesson 11B, medicines often work by binding to specific receptors in the body. Medicinal molecules must have the correct structure and properties to align with these receptors and maximise electrostatic interactions. For example, if a medicinal molecule needs to bind to a positively charged receptor in the body, it should contain partially negatively-charged functional groups positioned to optimally bind to this receptor and fit the 3D shape of the receptor. This is illustrated in figure 11.

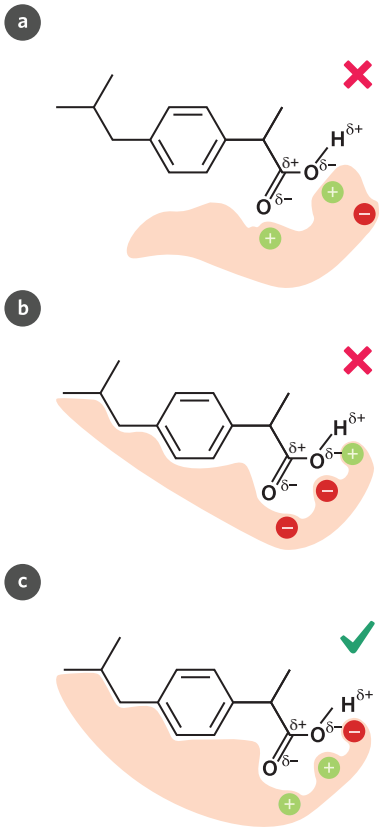


Figure 11 An ibuprofen molecule: **(a)** failing to bind to a receptor which is of unsuitable shape; **(b)** failing to bind to a receptor which has sites of unsuitable charge; and **(c)** binding to a receptor with the correct shape and charged sites

Although there is no 'universal' marker of medicinal molecules, many medicinal compounds:

- are relatively large molecules
- contain polar groups
- contain rings.

Rings may be saturated, with only single bonds between carbon atoms, or aromatic (like benzene, explored in lesson 7A), commonly represented with either alternating double and single bonds between carbon atoms or as a circle.

Rings give these molecules lots of flat surfaces, which provide plenty of sticking points to receptors, and are also easily modifiable, so when developing medicines, chemists can add functional groups to help bind to specific receptors. Polar groups are also very important, as they enable some medicines to dissolve and be absorbed by our bodies and hence act on the desired receptors. An example of a medicinal molecule's 3D structure is shown in figure 12.

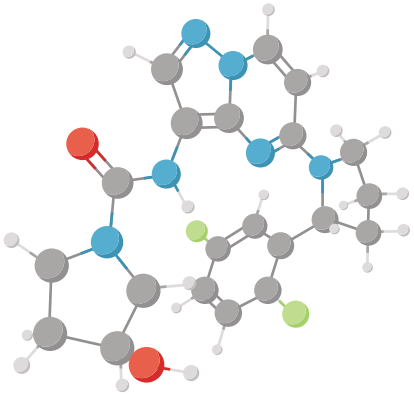


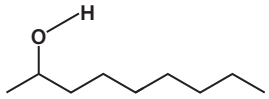
Figure 12 Ball-and-stick model of larotrectinib, an anti-cancer medicine with multiple polar groups and rings

PROGRESS QUESTIONS

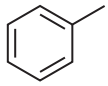
Question 4

Which of the following structures is most likely to be a medicinal molecule?

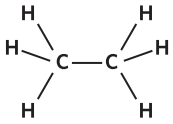
A.



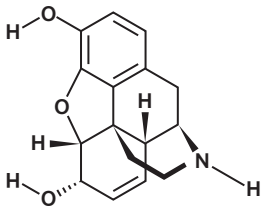
B.



C.

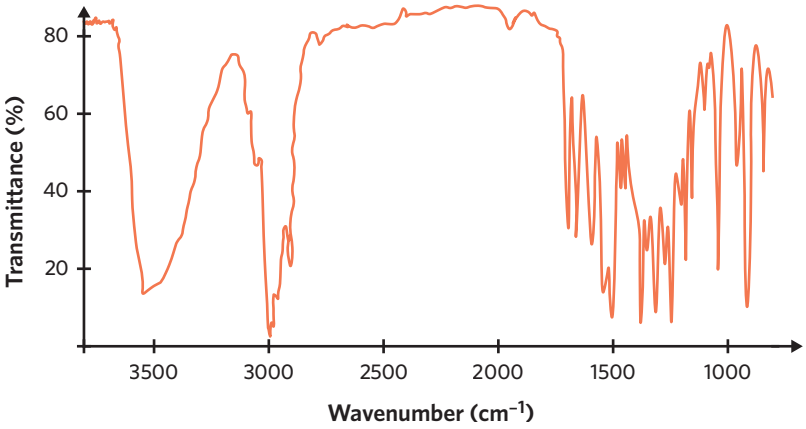


D.



Question 5

The following is an IR spectrum obtained for thymol, a plant compound noted for its antiseptic properties.



Which of the given groups is most likely to be present in thymol?

A. $-C{=}O$ **B.** $-NH_3$ **C.** $-OH$ **D.** $-COOH$

Chirality 4.2.14.1

Chirality is a property exhibited by some chemical compounds that is particularly important to the effectiveness of many medicinal molecules.

What is chirality?

Chiral compounds are compounds whose mirror image is not superimposable on the original compound. In other words, if an image of a chiral compound were mirrored and placed on top of the original image, the images would not align. Conversely, superimposable compounds (i.e. compounds that align with their mirror image) are described as **achiral compounds**. This concept is demonstrated through non-chemical objects in figure 13.

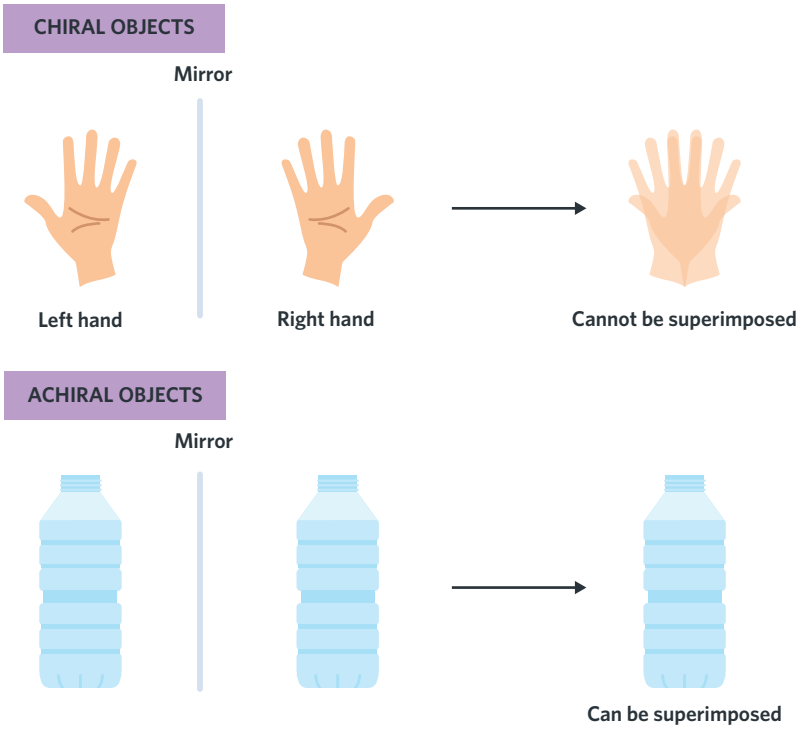


Figure 13 Chiral vs. achiral objects

Two isomers of a (chiral) molecule that are non-superimposable mirror images of each other are known as **optical isomers**, a type of stereoisomers (molecules with the same sequence of atoms but in a different spatial arrangement). For example, the green and red molecules shown in figure 14 are each other's mirror image, but are not superimposable on each other, making them optical isomers.

USEFUL TIP

Optical isomers are called 'optical' since they rotate polarised light in opposite directions (clockwise or anticlockwise).[1]

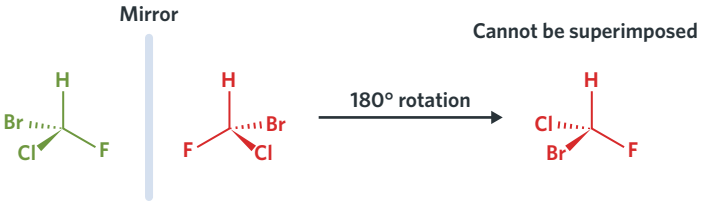


Figure 14 Non-superimposable mirror images of bromochlorofluoromethane

KEEN TO INVESTIGATE?

[1] **How do different sugars rotate polarised light in different directions?**
Search YouTube:
Optical rotation of sugars – chirality

All chiral molecules contain at least one **chiral centre**, which is an atom covalently bonded to four different groups. In the context of organic compounds, a chiral centre is most frequently a carbon atom, often referred to as a chiral carbon. When identifying chiral centres, it is vital to look for an atom attached to four different environments, and not just a carbon atom attached to four atoms. The general representation of a chiral carbon is shown in figure 15.

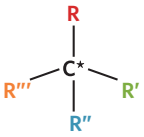


Figure 15 General representation of a chiral carbon, where C* is the chiral carbon, and R, R′, R″, and R‴ represent different environments

MISCONCONCEPTION

'Chiral centres are always carbon atoms.'

Although chiral centres are almost always carbon atoms, atoms such as nitrogen, phosphorus, and sulfur can also be chiral centres in rarer cases. For example, the narcolepsy medicine modafinil is chiral around a sulfur atom.

For example, to determine whether halothane (figure 16), a once-commonly used general anaesthetic, is chiral, first we need to assess whether either of the two carbon atoms are chiral centres.

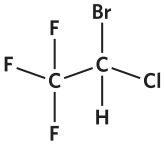


Figure 16 Structural formula of 2-bromo-2-chloro-1,1,1-trifluoroethane, commonly known as halothane

Figure 17a shows the four environments attached to C_1, which are −F, −F, −F, and −CBrClH. Since these are not all different (three are fluorine atoms) C_1 is not a chiral carbon. Figure 17b shows the four environments attached to C_2, which are −Br, −Cl, −H, and $-CF_3$. Since these are all different, C_2 is a chiral centre.

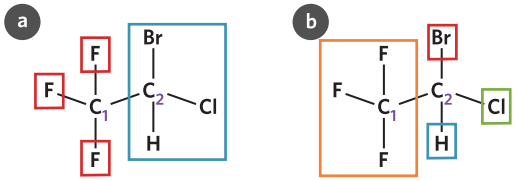


Figure 17 **(a)** Environments attached to C_1 and **(b)** environments attached to C_2

This means that the structural formula shown for halothane is non-superimposable on its mirror image, and so halothane is a chiral compound centred at C_2. These two optical isomers of halothane, *S*-halothane and *R*-halothane are shown in figure 18.

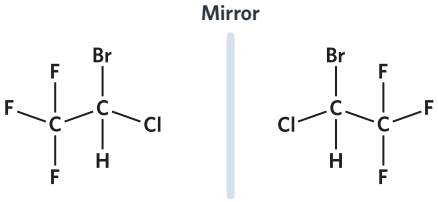


Figure 18 The two optical isomers of halothane; note that the two are mirror images of each other, yet one cannot be superimposed on the other, no matter which way it is rotated.

USEFUL TIP

Any carbon atom with a double or triple bond coming from it (including carbon atoms in aromatic rings) cannot be a chiral centre, so can be discounted straight away when searching for chiral centres.

USEFUL TIP

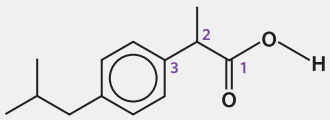
Pairs of optical isomers may be labelled in different ways, including *S*− and *R*−, *L*− and *D*−, + and −, left-handed and right-handed, or clockwise and anticlockwise. These abbreviations are beyond the scope of the study design.[2]

KEEN TO INVESTIGATE?

[2] **How are optical isomers named?**
Search: Naming enantiomers

WORKED EXAMPLE 2

Ibuprofen is a chiral molecule used as an anti-inflammatory medication to treat pain and fever. Which of carbon atoms 1, 2, and 3 is a chiral centre?



What information is presented in the question?

The skeletal formula of ibuprofen.

Ibuprofen is a chiral molecule.

Three candidate carbon atoms for a chiral centre.

What is the question asking us to do?

Determine which of the carbon atoms labelled 1, 2, and 3 is a chiral centre.

What strategies do we need in order to answer the question?

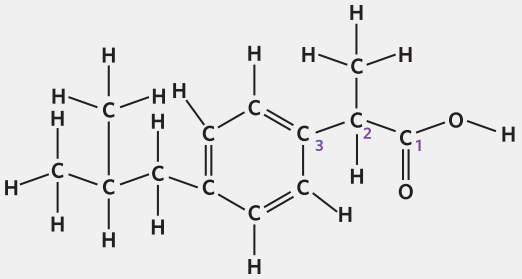
1. Draw the full structural formula of the molecule from the skeletal formula.
2. Identify the environments attached to each of the three possible carbon atoms.
3. Assess which of the three carbon atoms has four different environments attached to it.

Continues →

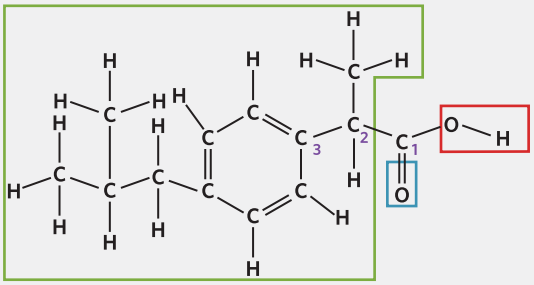
Answer

Recall that the hexagon around a continuous circle represents a six-carbon aromatic ring (like benzene). Since any carbon atom within an aromatic ring is never a chiral centre (as it is attached to a maximum of three unique environments), it is acceptable to represent an aromatic ring with alternating double and single bonds between carbon atoms for chiral centre identification.

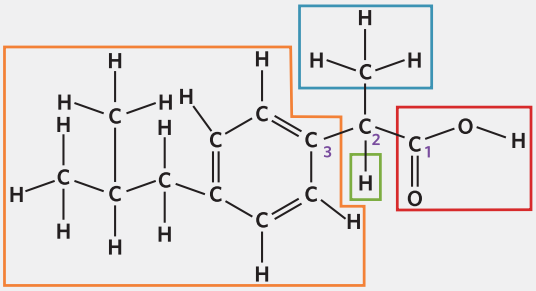
To identify chiral centres, first draw the full structural formula from the skeletal structure given.



Then, identify the environments attached to each of the three possible carbon atoms, starting from carbon atom 1.

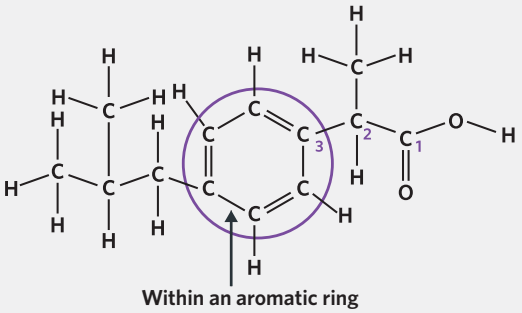


Due to the =O double bond, only three environments are attached to carbon atom 1, meaning carbon 1 is not attached to four different groups and, hence, cannot be a chiral centre. Next, consider carbon atom 2.



In this case, the four environments attached to carbon atom 2 (−H, $-CH_3$, −COOH, and −R, where R represents the remainder of the molecule) are all different, so carbon atom 2 is a chiral centre.

Lastly, consider carbon atom 3.



Since carbon atom 3 is within an aromatic ring, it is attached to a maximum of three environments and hence is not a chiral centre. Therefore, carbon atom 2 is a chiral centre, whereas carbon atoms 1 and 3 are not chiral centres.

Molecules may also have multiple chiral centres. In these cases, further steps are required to determine whether the molecule is chiral. In general, if a molecule with multiple chiral centres has a plane of symmetry (figure 19a), it is not chiral (it is achiral), as its mirror image is superimposable; if a molecule with multiple chiral centres has no plane of symmetry, it is chiral (figure 19b).

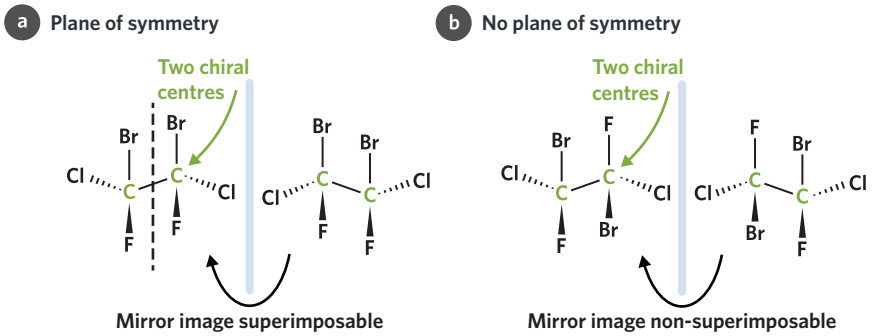
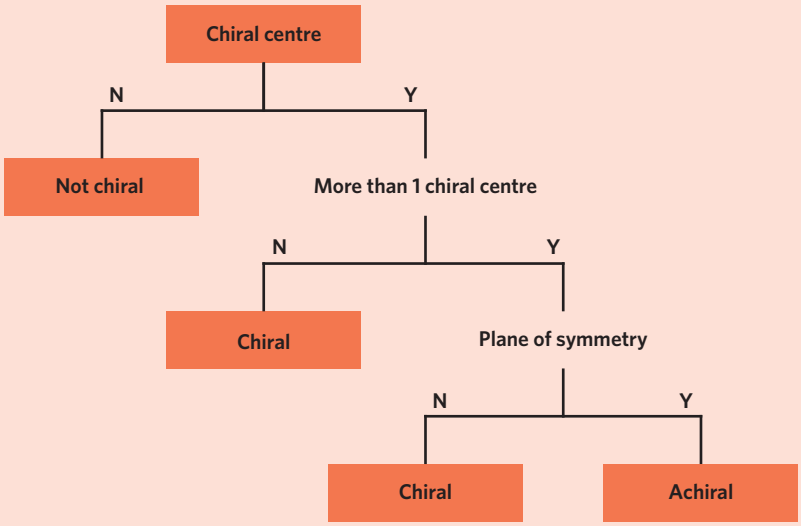


Figure 19 **(a)** Achiral and **(b)** chiral molecule with multiple chiral centres

STRATEGY

To determine if a molecule is chiral, use the following flowchart:



USEFUL TIP

All chiral molecules have at least one chiral centre; all molecules with exactly one chiral centre are chiral; but not all molecules with multiple chiral centres are chiral. In this way, chiral centres and chiral molecules are analogous to polar bonds and polar molecules respectively.

Why are optical isomers vital to the effectiveness of medicinal molecules?

Although optical isomers exhibit primarily the same physical properties, they may interact with other complex chemicals, such as those in our bodies, in vastly contrasting ways. For example, one optical isomer of a drug may have medicinal properties, yet the other optical isomer may have no effect at all, as demonstrated in figure 20.

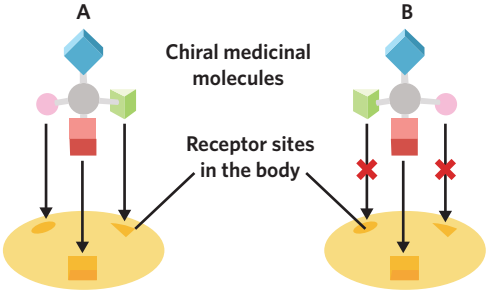


Figure 20 Optical isomer A binds to the receptor in the body, whereas optical isomer B does not.

KEEN TO INVESTIGATE?

[3] **How did thalidomide's optical isomerism cause thousands of deaths and deformities?**
Search YouTube:
Thalidomide: The Chemistry Mistake

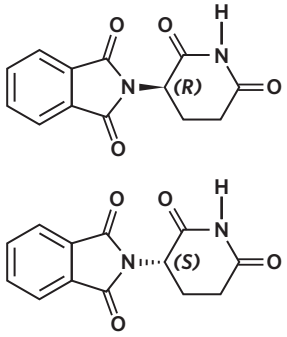


Figure 21 The two optical isomers of thalidomide; **(S)** (left) and **(R)** (right) denote the direction each optical isomer rotates a plane of polarised light.

An infamous example of this is the case of the medicine thalidomide (figure 21); its *R*- optical isomer is a safe and effective sedative, whereas its *S*- optical isomer causes tragic birth defects when administered to pregnant people.[3]

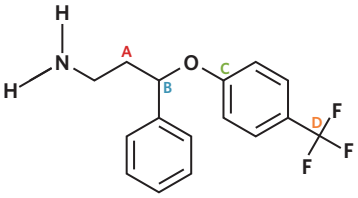
Optical isomers interact differently with the body because, as discussed, medicinal molecules must have a specific 3D shape and electrostatic interactions to bind with the desired receptors; the optical isomer of the medicine has a mirrored 3D shape and is thus unlikely to bind to the desired receptors. Instead, it may even bind to other receptors, often to negative effect. To draw an analogy, hands are optical isomers, as are gloves; a left glove generally fits a left hand well, yet wearing a right glove on a left hand will cause a very different (and likely uncomfortable) interaction. The same is true for many medicinal molecules: their two optical isomers may interact very differently with optically active receptors in the body.

As a result, it is often vital for pharmaceutical companies to select and isolate a specific optical isomer when producing medications, in order to ensure that the medicine acts as intended. To determine which optical isomer is present, we can test which direction the molecule rotates polarised light. However, many synthesis reactions of medicinal compounds produce a **racemate** or racemic mixture, a roughly 50/50 mixture of a compound's two optical isomers which is optically inactive (it does not rotate polarised light in a specific direction). Separation of a racemate is not always feasible, and this is a common cause of failure for potential medicines. Many medicines even 're-racemise' under biological conditions, meaning that the isolation of one optical isomer in the production process does not guarantee the safety or efficacy of the final product.

PROGRESS QUESTIONS

Question 6

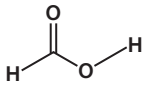
Which of the carbon atoms shown is a chiral centre?

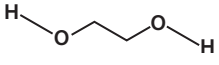


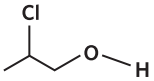
A. Carbon atom A
B. Carbon atom B
C. Carbon atom C
D. Carbon atom D

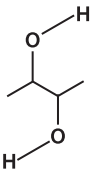
Question 7

Which of the following molecules is chiral?

A.


B.


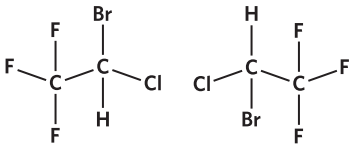
C.


D.


Continues →

Question 8

The two structures shown represent



A. structural isomers.

B. optical isomers.

C. the same compound.

D. neither isomers nor the same compound.

Question 9

Optical isomers of a medicine

A. bind with all receptors in the same way.

B. have identical physical properties.

C. always bind to different receptors from each other.

D. cannot always be separated from each other.

Theory summary

- The active ingredient in medicines is the compound that produces the desired effect on our body. For some medicines, the active ingredient is extracted from plants.
- Solvent extraction separates the desired compound from the source based on differing respective solubilities in two different, immiscible solvents.
- Once the desired compound has been extracted, it can be purified using distillation, a process in which the substance is heated and impurities are removed according to their different boiling points.
- Instrumental techniques – primarily HPLC, MS, IR, ^{1}H-NMR and ^{13}C-NMR – can be used to determine the structures of medicinal molecules and the typical functional groups present.
- Chiral molecules have a non-superimposable mirror image, and these two mirror images are referred to as optical isomers.
- A pair of optical isomers can be distinguished from each other by the direction in which they rotate a plane of polarised light.
- Often, two optical isomers of the same molecule have vastly different medicinal properties and degrees of effectiveness and safety, meaning that optical isomer selection is vital to the development and production of medicines.

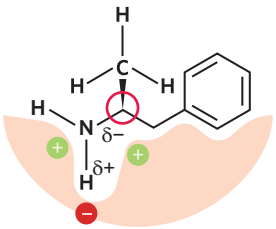
11A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 10–12.

Dextroamphetamine is a medicinal compound used to treat ADHD (attention deficit hyperactivity disorder). The diagram shown is a simplified representation of the binding of dextroamphetamine to a receptor in the body.



Question 10 (1 MARK)

The carbon circled in the structural formula above is attached to

A. one unique environment.

B. two unique environments.

C. three unique environments.

D. four unique environments.

Question 11 (1 MARK)

Dextroamphetamine is

A. chiral, because its mirror image is superimposable.

B. chiral, because it contains exactly one chiral centre.

C. achiral, because it contains no chiral centres.

D. achiral, because it contains multiple chiral centres yet has a plane of symmetry.

Question 12 (3 MARKS)

Consider the medicinal compound provided.

a. Explain whether optical isomerism could affect the ability of the compound to bind to this receptor in the body, and hence its effectiveness. 2 MARKS

b. Draw a diagram to support your answer 1 MARK

Exam-style

Question 13 (6 MARKS)

Tea tree leaves and the oil within them have been used by Aboriginal and Torres Strait Islander Peoples for thousands of years as a medicine to treat coughs and colds.

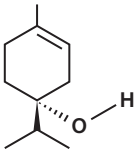
a. Explain briefly how

i. tea tree oil could be extracted and purified (note: tea tree oil is sensitive to high temperatures). 2 MARKS

ii. the compounds present in tea tree oil could be determined. 1 MARK

iii. the structures and functional groups of these compounds could be identified. 1 MARK

b. The major compound and potential active ingredient present in tea tree oil is terpinen-4-ol.

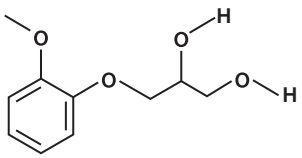


i. Identify the chiral centre in terpinen-4-ol. 1 MARK

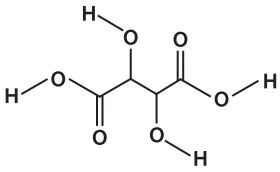
ii. Explain briefly how chirality can affect the effectiveness of medicinal molecules. 1 MARK

Question 14 (6 MARKS)

Guaifenesin and tartaric acid are two important compounds in cough medicines.



Guaifenesin



Tartaric acid

a. Identify the chiral centre(s) in:

i. Guaifenesin 1 MARK

ii. Tartaric acid 1 MARK

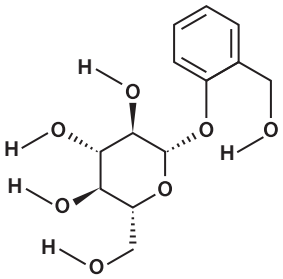
b. Identify and explain whether these molecules are chiral:

i. Guaifenesin 2 MARKS

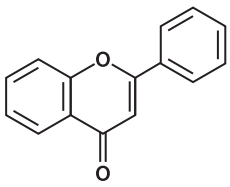
ii. Tartaric acid 2 MARKS

Question 15 (5 MARKS)

Aspirin is a commonly prescribed painkiller which can be derived from salicin (shown below) in willow tree extract.



Salicin



Flavone

Another compound present in willow tree extract is flavone.

The boiling points of these compounds are given in the table below.

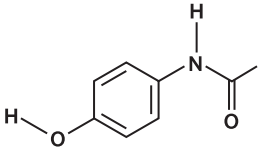
Compound	Melting point (°C)	Boiling point (°C)
Salicin	207	549
Flavone	97	367

a. Explain how solvent extraction could be used to isolate salicin from flavone, identifying particular solvents. 3 MARKS

b. Distillation can then be used to separate salicin from flavone. To what temperature should this mixture be heated to undertake distillation? Justify. 2 MARKS

Question 16 (8 MARKS)

Paracetamol is a medicine widely used to treat headaches and reduce fever. Its structure is shown.



a. Identify partial charges on any polar components in the molecule. 3 MARKS

b. Draw a diagram of a receptor to which paracetamol could bind, considering shape and electrostatic attractions. 2 MARKS

c. Is paracetamol chiral? Justify your answer. 2 MARKS

d. Predict whether the pictured molecule's mirror image would likely bind differently to a receptor in the body. 1 MARK

Key science skills

Question 17 (5 MARKS)

Tony is seeking to use steam distillation to extract the compound eucalyptol from eucalyptus leaves he has collected. Assume that all other compounds in eucalyptus leaves have a higher boiling point than eucalyptol.

a. There are a number of environmental factors that Tony must take into consideration.

i. Give one environmental factor regarding collection of leaves that Tony should consider. 1 MARK

ii. Give one environmental factor regarding steam distillation itself that Tony should consider. 1 MARK

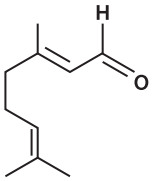
b. Outline a list of experimental method steps for Tony to use in his experiment. 3 MARKS

FROM LESSONS 12B & 12E

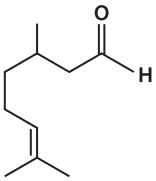
Questions from multiple lessons

Question 18 (7 MARKS)

Citral and citronellal are compounds present in oil extracted from lemon myrtle, a native Australian plant. These compounds have shown promising effectiveness as an insect repellent.



Citral

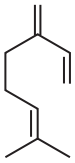


Citronellal

a. Give the systematic names of citral and citronellal. 2 MARKS

b. Evaluate and explain whether citral and citronellal could easily be separated from each other using solvent extraction or steam distillation. 3 MARKS

c. One impurity often found in lemon myrtle is myrcene.



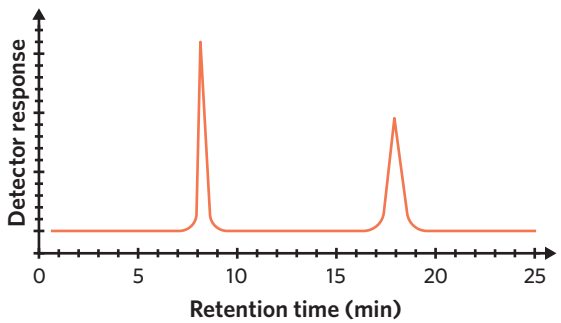
Myrcene

Explain how myrcene could be removed from a citral/citronellal mixture. 2 MARKS

FROM LESSONS 7B & 7C

Question 19 (10 MARKS)

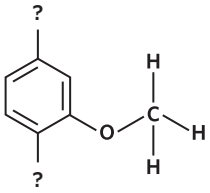
A group of researchers are investigating the properties of vanilla essence, a plant extract believed by some to have calming properties. Initially, HPLC is performed to determine the major compounds present. The HPLC results for vanilla extract, as well as those for some candidate compounds tested under identical conditions, are shown below.



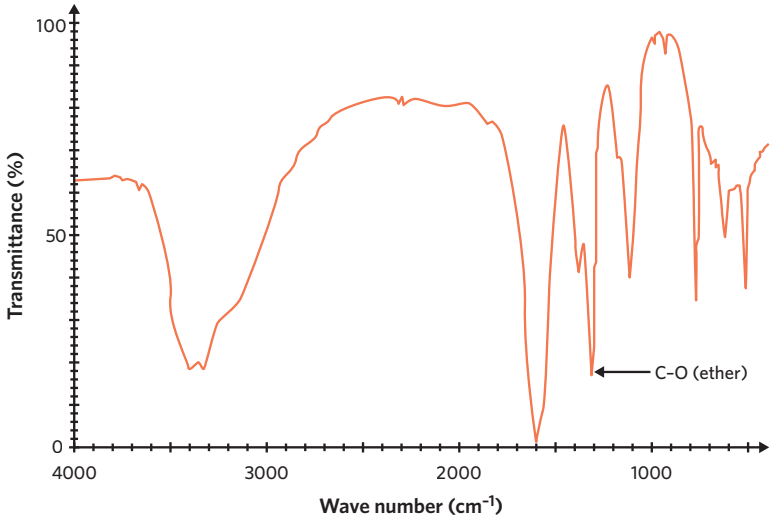
Compound	Retention time (mins)
Phenol	7
Vanillin	8
Coumarin	18
Glycerol	20

a. Besides vanillin, use the information provided to identify one other compound present in vanilla essence. Explain your answer. 2 MARKS

b. The researchers conduct a number of preliminary tests. From these, they determine that vanillin has empirical formula $C_xH_xO_3$ and the partial structure shown:

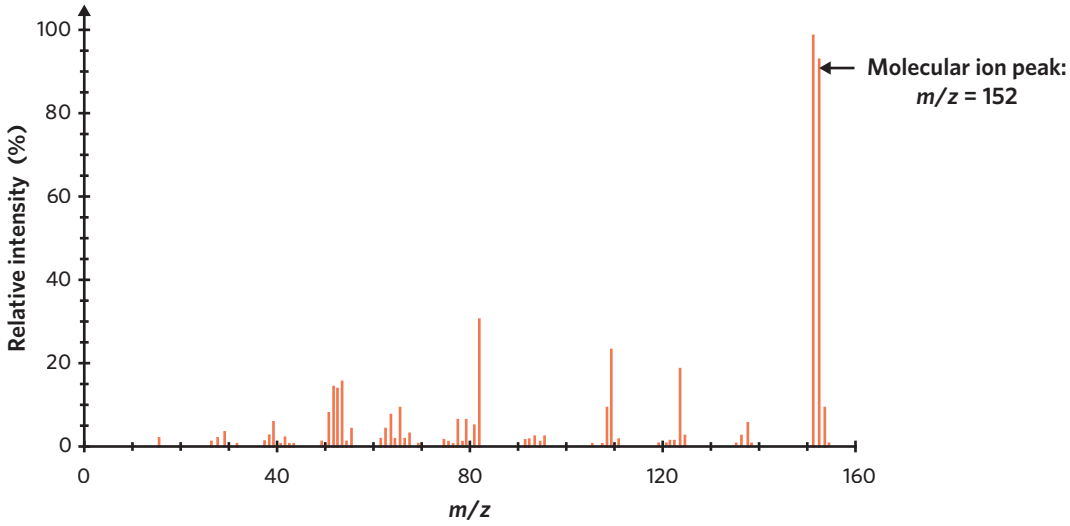


Vanillin was then analysed using infrared spectroscopy, producing the spectrum shown.



Identify two functional groups (besides the C—O—C ether group, labelled on the IR spectrum) potentially present in vanillin. Justify your choices using the information presented in the IR spectrum. 4 MARKS

c. The mass spectrum for vanillin was also determined.



Identify the molecular mass of the compound. 1 MARK

d. Using all the information provided:

i. Give the molecular formula of vanillin. 1 MARK

ii. Draw a possible skeletal formula of vanillin. 2 MARKS

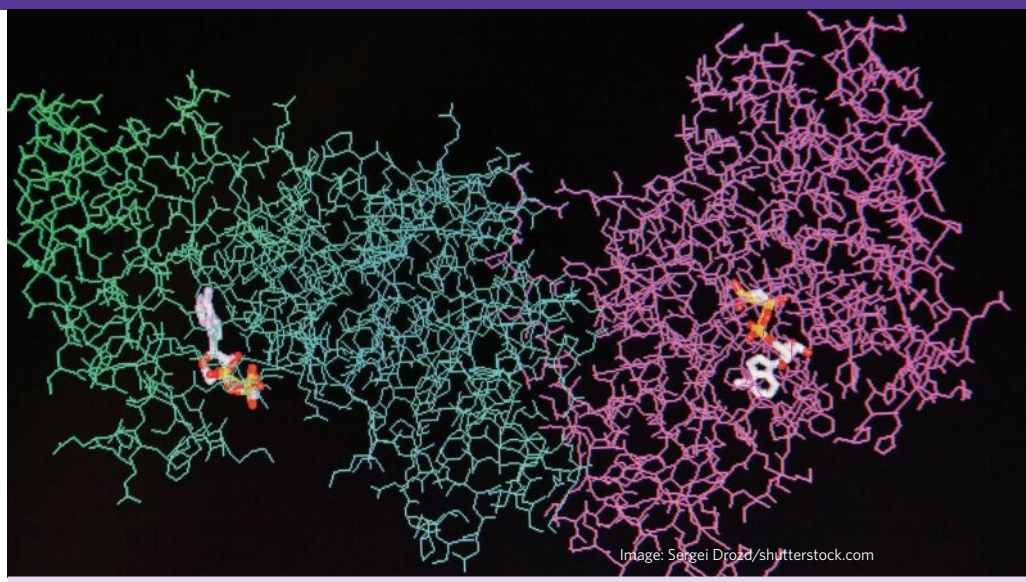
FROM LESSON 10F

Back to contents

11B Enzymes and medicines

STUDY DESIGN DOT POINT

- enzymes as protein-based catalysts in living systems: primary, secondary, tertiary and quaternary structures and changes in enzyme function in terms of structure and bonding as a result of increased temperature (denaturation), decreased temperature (lowered activity), or changes in pH (formation of zwitterions and denaturation)
- medicines that function as competitive enzyme inhibitors: organic molecules that bind through lock-and-key mechanism to an active site preventing binding of the actual substrate



How do some medicines actually work?

There are thousands of different **enzymes** found in human cells that are essential for a healthy life. These are often very complex molecules, and computers are often used to visualise these structures. As enzymes are classified as proteins, we will look at the different structural levels and how changes in conditions affect these structures, including how medicinal enzyme inhibitors control the catalytic activity of reactions in the body.

11A — 11B

- 4.2.15.1 The different protein structures
- 4.2.15.2 Principles of enzymes
- 4.2.15.3 Effect of temperature on enzyme function
- 4.2.15.4 Effect of pH on enzyme function
- 4.2.16.1 Medicinal enzyme inhibitors

ESSENTIAL PRIOR KNOWLEDGE

- 2-amino acid (α-amino acid)
- Amphiprotic
- 4A Rate of reaction

See questions 93 – 95.

KEY TERMS AND DEFINITIONS

Acidic amino acid amino acid with a carboxyl group in its side chain

Active site region of an enzyme where the substrate molecule binds to the enzyme and undergoes a chemical reaction

Basic amino acid amino acid with an amino group in its side chain

Competitive inhibitor molecule that competes with the substrate for binding to an active site in an enzyme

Denaturation process where proteins lose their quaternary, tertiary and/or secondary structure due to factors such as pH and temperature change

Deprotonation loss of a proton

Enzymes proteins which catalyse chemical reactions in living systems

Enzyme-substrate complex the unit which has the substrate bound to the active site of an enzyme

Lock-and-key model theory of enzyme-substrate binding where the substrate perfectly fits the active site of the enzyme

Optimal temperature temperature at which enzyme activity is at its greatest

Polypeptide chain chain of amino acids bonded by amide links (peptide bonds)

Primary structure linear sequence of covalently bonded amino acids in a polypeptide chain

Protonation gain of a proton

Quaternary structure combination of two or more interacting tertiary chains

Secondary structure arrangement of a primary protein structure in a way that results in an α-helix or β-pleated sheet due to hydrogen bonding

Substrate molecule which an enzyme acts upon

Tertiary structure overall three-dimensional structure of a protein

Zwitterion neutral molecule that has a positively charged $-NH_3^+$ and a negatively charged $-COO^-$ on the number two carbon

The different protein structures 4.2.15.1

As we learned in lesson 8A, proteins are made up of repeating units called amino acids. These building blocks are responsible for the four main types of structures found in proteins:

- primary
- secondary
- tertiary
- quaternary.

How are the four types of protein structure formed?

Primary structure

The simplest level of protein structure, the **primary structure**, is a sequence of amino acids linked by covalent bonds (called either amide links, amide bonds or peptide bonds) in a linear **polypeptide chain** (figure 1). As there are 20 different types of amino acids, a number of different polypeptide chain combinations can be formed.

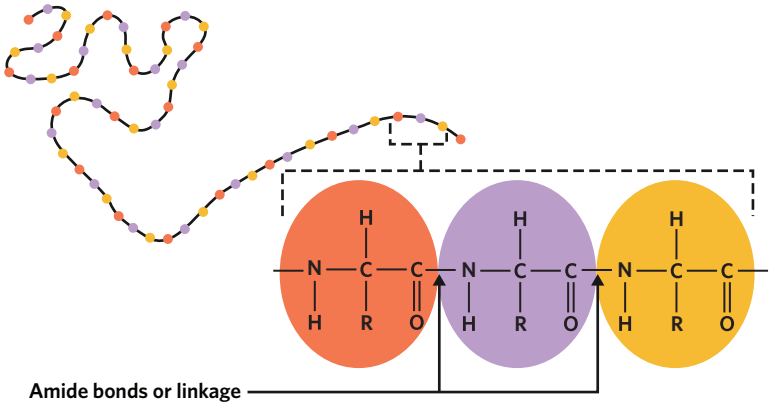


Figure 1 Covalent bonds between carbon and nitrogen create the primary structure in proteins.

USEFUL TIP

Amino acids are linked by a special type of covalent bond called an amide bond; this bond is a functional group and can also be referred to as an amide linkage or a peptide bond.

Secondary structure

The next level of protein structure, the **secondary structure**, occurs when the polypeptide chains that form the primary structure fold into different shapes as a result of hydrogen bonding within the polypeptide chain. There are two main types of secondary structures:

- The α-helix structure is stabilised by the hydrogen bonds formed between the oxygen of the C=O group in each peptide bond and the hydrogen of the N−H group in the peptide bond four amino acids below it in the helix (figure 2.1).
- A β-pleated sheet is formed by linking two or more adjacent sections of the polypeptide by hydrogen bonds between the oxygen in one peptide bond and the hydrogen in the other peptide bond (figure 2.2).

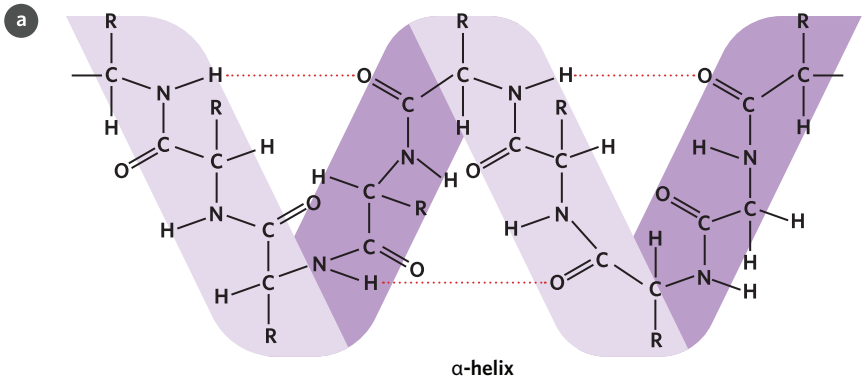


Figure 2.1 Hydrogen bonds (dotted red lines) create the secondary structure **(a)** α helix.

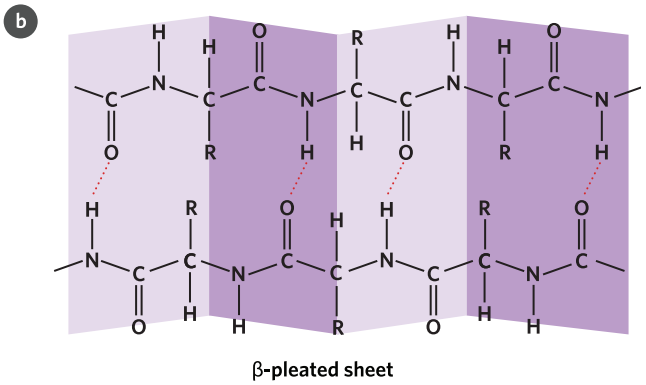


Figure 2.2 Hydrogen bonds (dotted red lines) create the secondary structure **(b)** β-pleated sheet.

Tertiary structure

The **tertiary structure** is the overall 3D shape of a polypeptide chain. A tertiary structure is stabilised by a combination of the forces shown in table 1.

Table 1 Forces that hold the tertiary structure of a protein together

Type of force	Example of attractions (figure 3)	Energy required to break attraction (kJ mol^{-1})
Ionic interactions	a) NH_3^+ and COO^- on adjacent side chains	Varies greatly: ~100-600
Disulfide bridges (a type of covalent bond)	b) Two cysteine −SH side chains only	~250
Hydrogen bonds	c) N and H, O and H	~20
Dispersion forces	d) Non-polar side chains	~1-5

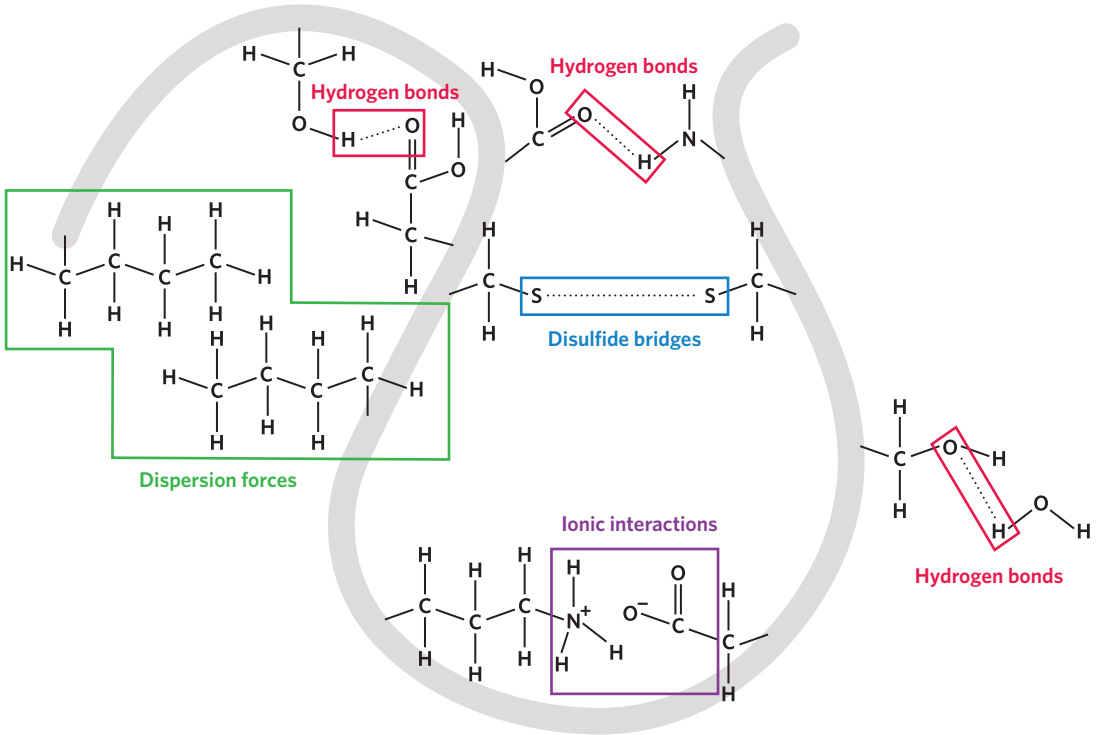


Figure 3 Different combinations of electrostatic forces of attraction create the tertiary structure.

Not all tertiary structures will contain each type of electrostatic force of attraction; it will depend on the type of side chain present in the amino acids. The tertiary structure of a protein is considered to be the functional structure of protein; hence, proteins will lose their functions if their tertiary structures are disrupted.

The unique properties of each side-chain – and thus the many different interactions possible between them – give rise to the vast range of structures and functions of proteins in the body.

Quaternary structure

The **quaternary structure** comprises the combination and interactions between two or more tertiary chains (figure 4). It is important to note that not all proteins have quaternary structures.

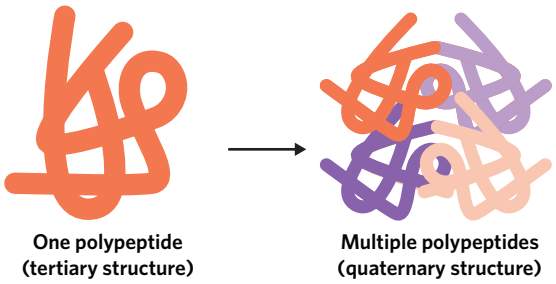


Figure 4 Quaternary structures are held together by the same forces as the tertiary structure.

USEFUL TIP

Although dispersion is the weakest force in general, it actually has the largest effect on protein folding. Recall that dispersion strength increases as molecule size increases. Proteins are very large molecules, meaning dispersion forces have significant effects on the tertiary and quaternary structures.

PROGRESS QUESTIONS

Question 1

Aside from the 'R' side chain, the functional groups found in an amino acid are

A. amino and hydroxyl groups.
B. amino and carboxyl groups.
C. carbonyl and ester groups.
D. carboxyl and amide groups.

Question 2

The type of force(s) present in the tertiary structure of a protein are

A. dispersion.
B. ion-ion.
C. covalent.
D. All of the above

Question 3

When referencing the structures of proteins, hydrogen bonds can be found only in

A. primary structures.
B. α–helices and primary structures.
C. primary structures and tertiary structures.
D. α–helices, β–pleated sheets, tertiary structures and quaternary structures.

Principles of enzymes 4.2.15.2

Enzymes are biological catalysts made of proteins that play an essential role in the functioning of the human body.

How do enzymes alter the rate of reaction?

Enzymes are crucial to the body's function as they catalyse chemical reactions necessary to sustain life that would otherwise occur too slowly. Specifically, an enzyme catalyses a reaction by providing an alternate reaction pathway that requires a lower activation energy. This has been covered in chapter 4 and is shown in the energy profile diagram in figure 5.

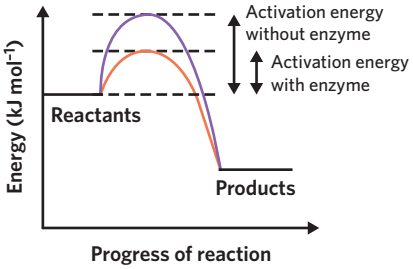


Figure 5 Enzymes can lower the activation energy of specific reactions.

An enzyme functions by binding to the reactant(s) of a reaction, known as the **substrate**. The region of the enzyme to which the substrate binds is known as the **active site** (figure 6).

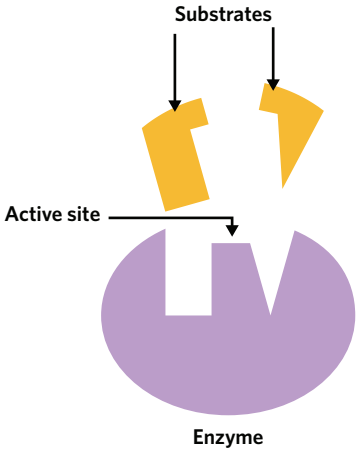


Figure 6 The general model of an enzyme and substrates

USEFUL TIP

The word 'bind' applies to electrostatic forces of attraction that are both reversible (temporary attraction) and irreversible (bond).

MISCONCEPTION

'Enzymes are used up in reactions.'

Enzymes are not used up in the reactions they catalyse and do not change the yield of a reaction - they simply speed up the rate of reaction.

Unlike inorganic catalysts, enzymes are highly specific in that each enzyme is only responsible for catalysing one or a small number of chemical reactions. This explains why there is an immense number of different enzymes catalysing reactions in the body.

The size, shape, chemical behaviour, and three-dimensional nature of the active site is very important to the functioning of the enzyme, as for the substrate to successfully bind to the active site, the substrate must form a temporary bond with the enzyme.

USEFUL TIP

Enzymes can be categorised as either positive or negative catalysts. A positive catalyst increases the rate of a reaction, whilst a negative catalyst decreases the rate. Negative catalysts are also known as inhibitors.

One of the major models[1] that scientists have developed to explain enzyme activity is the **lock-and-key model** which, as the name suggests, is where the substrate fits perfectly into the active site of the enzyme, just as a key perfectly fits a lock. As shown in figure 7, the shape of the substrate is perfectly complementary to the shape of the enzyme's active site. After successful binding, the entire structure is known as an **enzyme-substrate complex**. As a complex, the enzyme's action will begin, which may catalyse a reaction breaking down larger molecules into smaller ones, or building larger molecules from smaller ones. After the reaction has occurred, the enzyme will release the substrate and it is free to bind to a new substrate.

KEEN TO INVESTIGATE?

1 **What is the other main model used to explain the function of enzymes?**
Search: Models of enzyme function

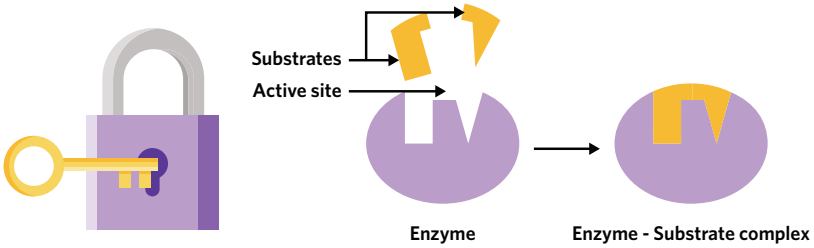


Figure 7 The lock-and-key model

PROGRESS QUESTION

Question 4

The lock-and-key model states that

A. an enzyme will change the shape of its active site to fit the substrate.

B. the substrate perfectly fits the enzyme's active site.

C. an enzyme cannot differentiate between isomers.

D. an enzyme can only be used once.

Effect of temperature on enzyme function 4.2.15.3

Enzyme activity is heavily dependent on the temperature of the chemical reaction.

How do different temperatures affect the function of enzymes?

As discussed in lesson 4A, an increase in temperature causes an increase in the rate of reaction. However, the activity of enzymes does not always increase in response to an increase in temperature.

As we can see in figure 8, as temperature increases, there is a general increase in enzyme activity. This is consistent with our knowledge of reaction rates, because at higher temperatures, not only is the average kinetic energy of the particles greater, but there are also more collisions per unit of time between enzymes and their respective substrate. However, after reaching the **optimal temperature** – the temperature at which an enzyme's activity is at its greatest – the enzyme activity begins to decrease rapidly, and eventually reaches zero. We can explain this in terms of the chemical composition of enzymes:

- Enzymes are proteins and will therefore be denatured at high temperatures.
- **Denaturation** is the process whereby the secondary, tertiary, and quaternary (if applicable) structures of the enzyme, which define the shape of the active site, are disrupted by the increase in temperature (figure 9).
- Lower temperatures do not denature the enzyme; rather, activity is minimised and protein stability is maximised.

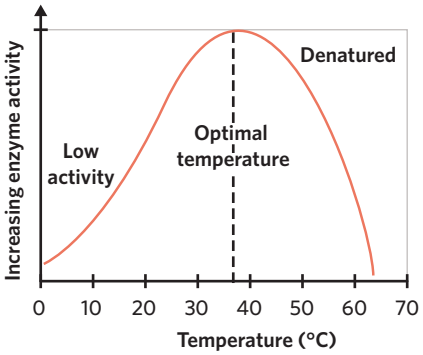


Figure 8 Graph of enzyme activity and temperature in humans

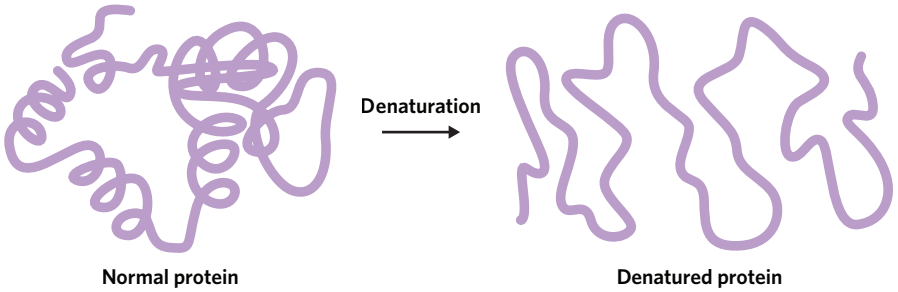


Figure 9 Denaturation of a protein's structure at high temperatures

Denaturation causes irreversible structural damage, meaning the enzyme is unable to function again; however at lower temperatures, the enzyme is not irreversibly damaged. Therefore, the function of an enzyme is very sensitive to temperature changes.

PROGRESS QUESTIONS

Question 5

When an enzyme is heated to 75 °C, the part of the enzyme's structure that will be least affected is the

A. primary structure.

B. secondary structure.

C. tertiary structure.

D. quaternary structure.

Question 6

An enzyme

A. is denatured at low temperatures.

B. is consumed in a reaction.

C. is always active.

D. is usually specific to a certain substrate.

Effect of pH on enzyme function 4.2.15.4

pH can denature an enzyme's tertiary (and quaternary if present) structure, impacting its binding capability to a substrate. Enzyme activity is also dependent on the pH of the environment in which it functions due to the effect of pH on the charges of certain functional groups.

How do changes in pH affect the function of an enzyme?

As we have learned so far, the active site of an enzyme binds to a substrate. Figure 10 illustrates the important role that the side groups of amino acids play in this temporary act of binding.

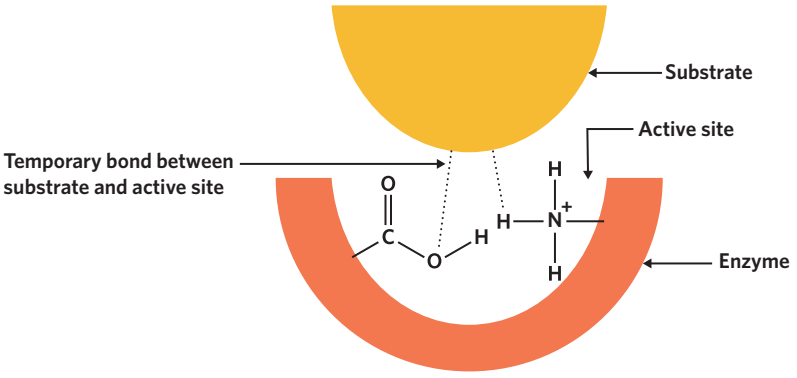


Figure 10 Interaction between substrate and amino acid side groups in the active site

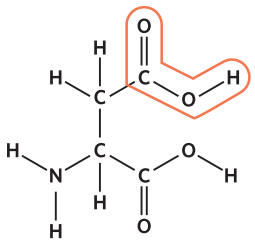


Figure 11 Aspartic acid has a carboxyl functional group in its side chain.

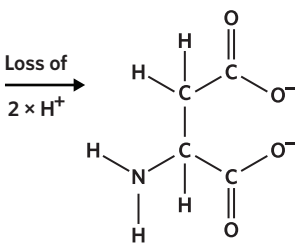


Figure 12 The deprotonation of aspartic acid from figure 11 to give a net charge of −2

The properties of the side groups on different amino acids are very important – in particular, whether they are acidic or basic.

An **acidic amino acid**, such as aspartic acid in figure 11, has a carboxyl group in its side chain, as circled on the figure.

As such, in a very basic solution where the pH is greater than 13, each carboxyl group will lose a hydrogen atom, giving aspartic acid a doubly negative charge as shown in figure 12. This process, known as **deprotonation**, occurs when a large number of OH^- ions are present.

Furthermore, a **basic amino acid**, such as lysine in figure 13, has an amino functional group in its side chain, circled on the figure.

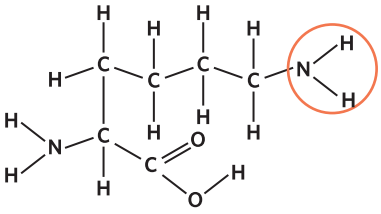


Figure 13 Lysine has an extra amino functional group.

In a very acidic solution, where the pH is less than 1, the two amino groups in lysine will each gain a proton and become doubly positively charged, as shown in figure 14. This process, termed **protonation**, occurs when a large number of H^+ ions are present.

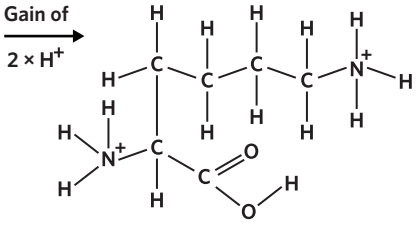
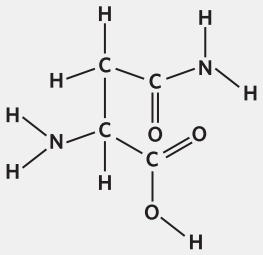


Figure 14 The protonation of lysine from figure 13 to give a net charge of +2

WORKED EXAMPLE 1

The structural formula of the amino acid asparagine is shown.
Draw the structural formula of asparagine at a pH of 1.0.



What information is presented in the question?

The structure of the amino acid asparagine.

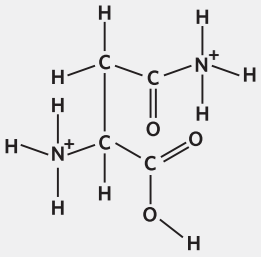
What is the question asking us to do?

Draw the structure of the amino acid when the pH is 1.0.

What strategies do we need in order to answer the question?

1. Determine whether the concentration of H^+ or OH^- is high when the pH is low.
2. Based on step 1, determine whether the NH_2 group or COOH group is altered.
3. Draw the structure of the amino acid based on step 2.

Answer



When the pH is low, an amino acid has as many H^+ added to it as possible. All bonds must be shown in a structural formula. The asparagine now has an overall net charge of +2.

A change in the pH in the enzyme's environment may alter enzyme activity due to:

- changes in the charges of the side chains of an enzyme's constituent amino acids, shown in figure 10 and figure 12
- different interactions between an enzyme and its substrate due to disruption to the enzyme's tertiary structure
- secondary, tertiary, and quaternary forces that maintain the structures being disrupted, causing denaturation.

Consequently, most enzymes function only in a narrow pH range.

How are zwitterions formed?

All amino acids are amphoteric, meaning they can accept or donate a proton depending on the pH of the environment. In an environment of neutral pH, where $[H^+] = [OH^-]$, neither the protonated or deprotonated species dominates. Instead, the NH_2 group can accept a H^+, forming NH_3^+, and the COOH group can donate its H atom, forming COO^-.

KEEN TO INVESTIGATE?

2 What is the isoelectric point of zwitterions?
Search YouTube:
Are zwitterions charged?

This results in the formation of a **zwitterion** due to the presence of both a negative and positive charge on functional groups attached to the second carbon; hence, zwitterions have no net charge. This idea is summarised in figure 15. It is important to note that different amino acids change in structure at a different pH level.[2]

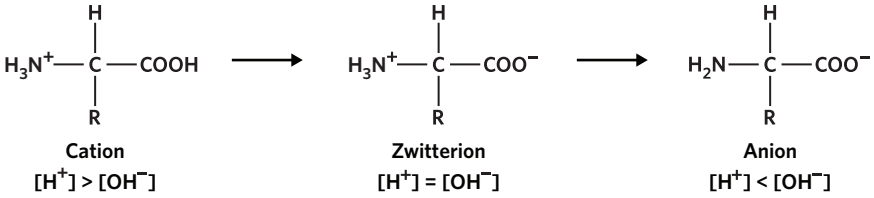


Figure 15 The structure of an amino acid depends on the pH of the solution.

WORKED EXAMPLE 2

Met-enkephalin is a small protein found in the central nervous system and the gastrointestinal tract of the human body. Which of the following are the correct structures for the two terminal ends of met-enkephalin at a very low pH?

A.	$-NH_2$	$-COOH$
B.	$-NH_2$	$-COO^-$
C.	$-NH_3^+$	$-COO^-$
D.	$-NH_3^+$	$-COOH$

What information is presented in the question?

The pH is low and the chemical is a protein and so has an amino acid structure.

What is the question asking us to do?

Identify the terminal groups of this protein.

What strategies do we need in order to answer the question?

1. Determine whether the concentration of H^+ or OH^- is high when the pH is low.
2. Based on step 1, determine whether the NH_2 group or COOH group is altered.

Answer

D. α-amino acids or 2-amino acids have the general structure $H_2NCH(R)COOH$. At very low pH, i.e. in acidic solutions, basic $-NH_2$ groups become protonated to form $-NH_3^+$ groups. At low pH $-COOH$ groups are unaffected. So, the correct structures for the terminal ends of met-enkephalin and any protein are $-NH_3^+$ and $-COOH$.

Adapted from VCAA 2016 exam Multiple choice Q11

PROGRESS QUESTIONS

Question 7

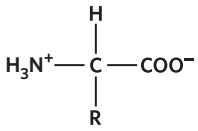
Which of the following statements is **incorrect** regarding enzymes?

A. Enzyme activity differs with a change in temperature.
B. Enzymes are biological catalysts.
C. Enzymes are consumed in chemical reactions.
D. Enzyme activity differs with a change in pH.

Continues →

Question 8

The following structure is an example of a



A. tertiary structure.

B. quaternary structure.

C. zwitterion.

D. protein.

Medicinal enzyme inhibitors 4.2.16.1

Many of the small-molecule medicines approved by the Therapeutic Goods Administration (TGA - Australia) are **competitive inhibitors** of enzymes. These molecules can 'mimic' an enzyme's usual substrate by being similar in shape and chemical property, and therefore fit into the active site and block the binding of the substrate.

How do some enzyme inhibitors work?

Angiotensin-Converting-Enzyme Inhibitors (ACEIs)

ACEIs are some of the most widely used enzyme inhibitors in modern medicine. They are used to treat hypertension (also known as high or raised blood pressure), heart failure, diabetes, and kidney disease.

Mechanism of action

As the name suggests, ACE inhibitors work by inhibiting the angiotensin-converting enzyme that leads to smooth muscle contraction (figure 16). This is the cause of hypertension, a condition in which the blood vessels have consistently raised pressure, which is a major cause of heart-attacks and strokes.

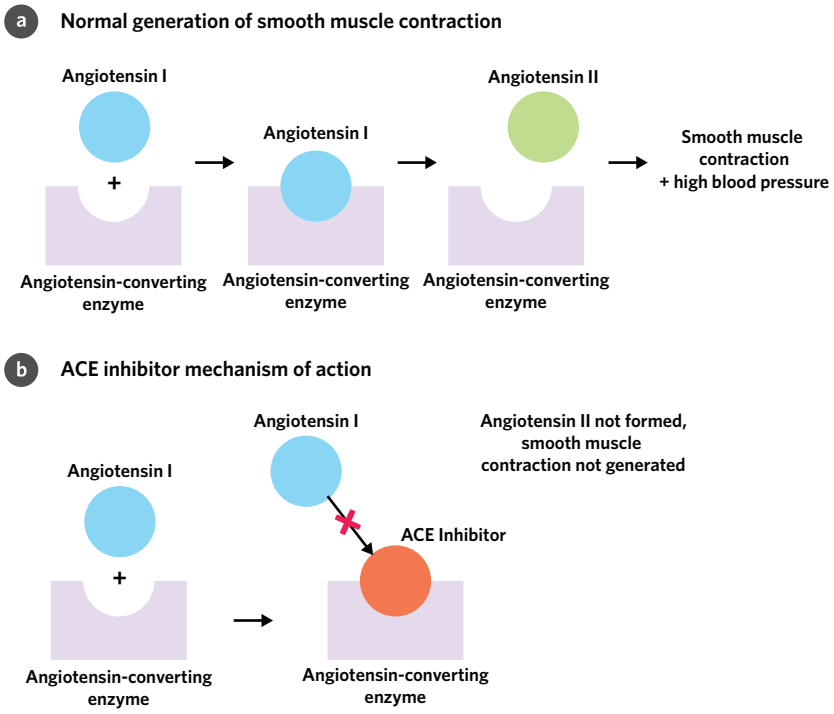


Figure 16 **(a)** Using the lock-and-key model to show the normal process **(b)** and mechanism of action of ACEIs

Donepezil

Donepezil is a competitive, reversible enzyme inhibitor used for the treatment of Alzheimer's. Alzheimer's is a brain disease that gradually destroys memory and cognitive skills. Alzheimer's is associated with decreased acetylcholine levels and donepezil selectively inhibits the enzyme that breaks down acetylcholine (called acetylcholinesterase - this enzyme has two active sites, one exhibiting ion-ion interactions and one exhibiting hydrogen bonding with the substrate). Figure 17 shows the normal process by which acetylcholine is broken down in the body and figure 18 models how donepezil inhibits this process.

Mechanism of action

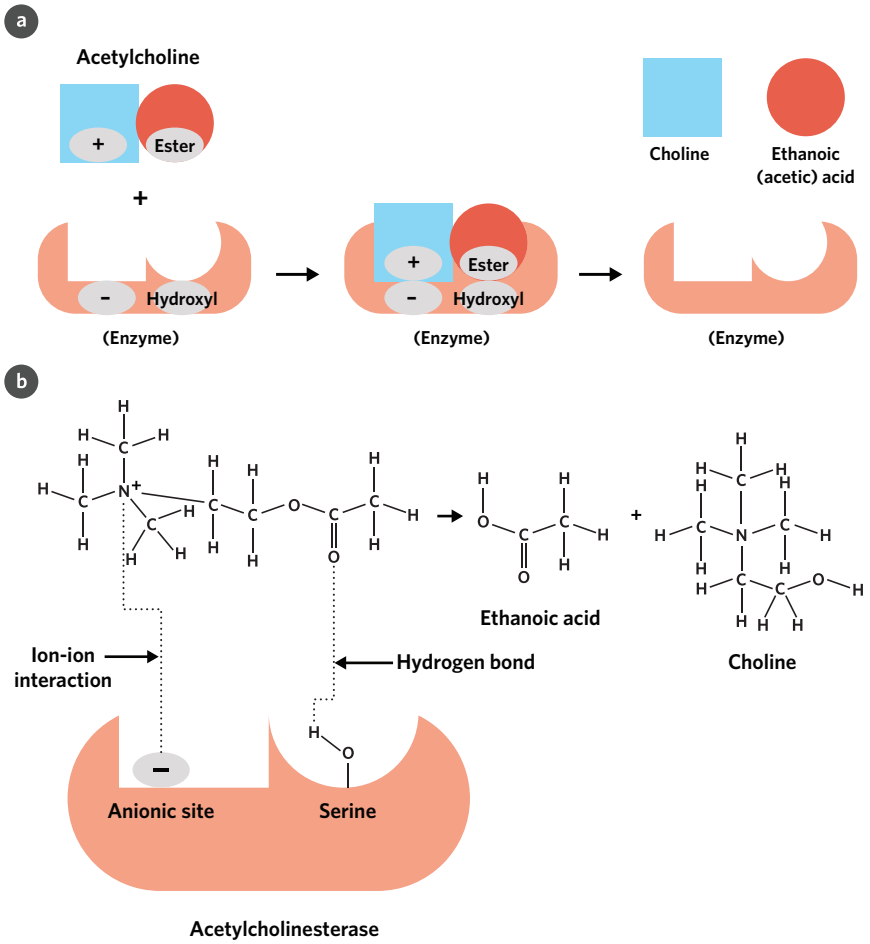


Figure 17 The lock-and-key model **(a)** and structural formula **(b)** can be used to show the normal breakdown of acetylcholine.

Donepezil mechanism of action

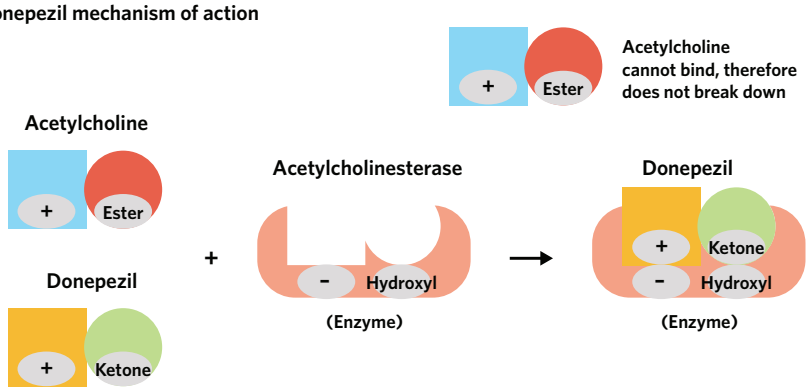


Figure 18 Lock-and-key model of donepezil inhibiting the breakdown of acetylcholine

PROGRESS QUESTIONS

Question 9

Enzyme inhibitors work by

A. increasing the activation energy.

B. decreasing the activation energy.

C. binding to active sites.

D. creating a second active site.

Theory summary

- There are four levels to the structure of a protein: primary, secondary, tertiary, and quaternary.
- The lock-and-key model proposes that a substrate fits perfectly into the active site of an enzyme.
- Enzymes are biological catalysts which consist of an active site which binds to a substrate.
- Enzymes require the exact physical (3D shape) and chemical (electrostatic attractions) characteristics to function with a specific substrate.
- An increase in temperature increases the enzyme activity up to the optimal temperature, above which there is a sharp decrease in activity due to denaturation of the enzyme.
- A decrease in temperature lowers enzyme activity but does not denature it.
- The charges of an amino acid change depending on the pH of the solution:
  - In an acidic solution, amino acids appear as a cation.
  - In a basic solution, amino acids appear as an anion.
  - In a neutral solution, amino acids appear as a zwitterion.
- When an amino acid is in the form known as a zwitterion, it has both positive and negative charges on the second carbon atom, with no net charge (the side-chains are not charged in a zwitterion).
- A change in pH can affect enzyme function by causing an enzyme to become denatured, as the H^+ or OH^- disrupt the forces that maintain the specific shape of the enzyme.
- Many medicines work by competitively (and reversibly) inhibiting important enzymes in the body, improving the quality of life for millions of humans.

11B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 10–12.

Consider the following statements about the structure of proteins.

I. The primary structure of a protein is determined by the sequence of amino acid residues.

II. The secondary structure of a protein is the result of hydrogen bonding between −N−H and −C=O groups.

III. The tertiary structure of a protein involves bonding between the side chains on the amino acid residues.

Question 10 (1 MARK)

The primary structure of amino acids in a polypeptide chain is held together by

A. hydrogen bonds. **B.** covalent bonds. **C.** ionic bonds. **D.** metallic bonds.

Question 11 (1 MARK)

The secondary structure of a protein is determined by

A. dispersion forces. **B.** ionic interactions. **C.** hydrogen bonds. **D.** disulfide bridges.

Question 12 (1 MARK)

Of these statements

A. only I and III are true. **B.** only I and II are true. **C.** only II and III are true. **D.** I, II, and III are all true.

VCAA 2012 Exam 1 Multiple choice Q5

Exam-style

Question 13 (1 MARK)

Botox is a neurotoxic protein that causes paralysis. The toxin acts by disrupting the disulfide bonds of cell receptors, which are made from proteins. By doing so, botox disrupts the

A. primary structure. **B.** secondary structure. **C.** tertiary structure. **D.** All of the above

Question 14 (1 MARK)

Which of the following does not affect the rate of a reaction involving enzymes?

A. A change in pH

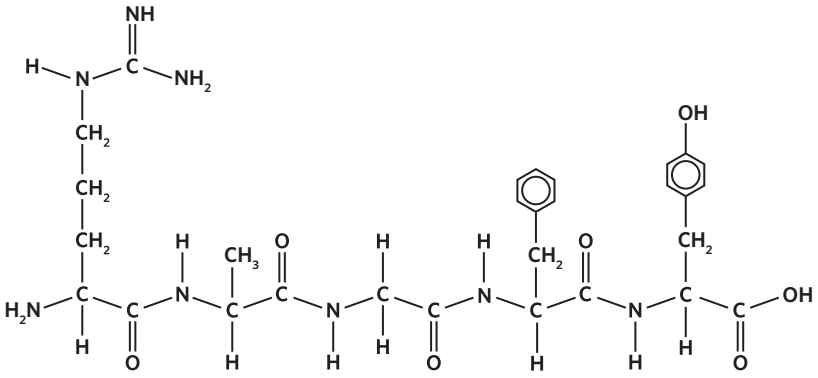
B. An increase in the concentration of an enzyme when all the substrate molecules are bound

C. A change in temperature

D. An increase in the concentration of an enzyme when not all the substrate molecules are bound

Question 15 (1 MARK)

The number of amide bonds (linkages) in the following polypeptide is



A. 2 **B.** 3 **C.** 4 **D.** 5

Question 16 (1 MARK)

More than 200 million people worldwide rely on taking statins to help improve their heart health. Statins lower artery-clogging cholesterol by inhibiting enzymes involved in the synthesis of cholesterol. They do this by competing with a chemical precursor to cholesterol for the active site of the HMG-CoA reductase enzyme.

Given that the body does need a small amount of cholesterol to function, medicinal enzyme inhibitors used to treat high cholesterol must be

A. cheap and easy to manufacture.

B. readily available and easily distributed.

C. irreversible competitive inhibitors.

D. reversible competitive inhibitors.

Question 17 (3 MARKS)

Alanine behaves differently depending on the environment of the solution to which it is added. It has the formula $CH_3CH(NH_2)COOH$.

a. Draw the structural formula of alanine in a solution with a pH of 9. 1 MARK

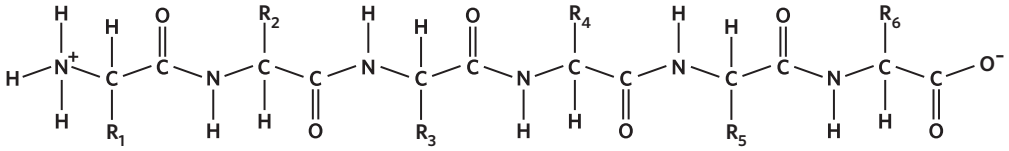
b. Alanine is commonly found in β-pleated sheets. Describe the bonds that contribute to maintaining this structure. 2 MARKS

Question 18 (4 MARKS)

The DNA in our cells gives instructions for the production of functional proteins found in our body. This process occurs progressively in different areas of the cell. Depending on the stage, the structure of the protein can look different.

The image below shows different forms of the same protein.

i.



ii.



iii.



iv.



Identify the name of each structure and the bonds that hold each structure together.

Key science skills

Question 19 (7 MARKS)

Boglárka, a VCE chemistry student, would like to determine the effect of pH on enzyme activity. They use the enzyme lipase which is essential in the breakdown of lipids. This enzyme has an optimum pH range of 4.0–5.0, and they set up 3 test tubes each with a few drops of lipase. One test tube has a pH of 1.0, the second has a pH of 4.5, and a third has a pH of 14.0. Boglárka then places a cube of fat of the same size in each test tube.

a. Using your knowledge of pH and enzyme activity, predict what Boglárka would observe in each test tube, justifying your reasons. 2 MARKS

b. Does this experiment have control test tubes? If not, explain what could be done to improve the validity of the results. 2 MARKS

c. The enzyme α-amylase is produced by the salivary glands and secreted into the mouth. Explain why α-amylase can only function in the mouth, given that different parts of the digestive tract all vary with respect to pH. 2 MARKS

d. What structure(s) of a protein is changed when an enzyme becomes denatured? 1 MARK

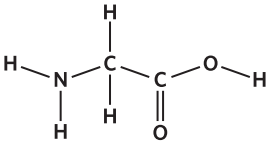
FROM LESSON 12D

Questions from multiple lessons

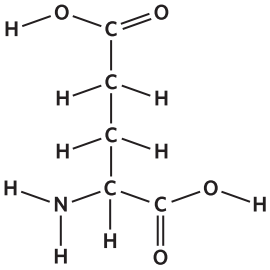
Question 20 (3 MARKS)

Due to the trends of supplemented protein intake, many foods claim to have increased levels of protein.

Dominykas wanted to determine the protein content in a packet of chips that claimed to have 'only added glycine and glutamic acid'.



Glycine



Glutamic acid

a. After some extraction techniques, Dominykas conducted mass spectrometry on the sample. He found that the molecular ion had a mass to charge ratio of 147 m/z. Identify the amino acid that was present in his sample. 1 MARK

b. To confirm, Dominykas made another sample of his chips for HPLC analysis. Given that a polar stationary phase was used, which amino acid - glycine or glutamic acid - would have the greatest retention time? Explain. 2 MARKS

FROM LESSONS 10A & 10E

Question 21 (7 MARKS)

The following is a student's summary of catalysts. It contains some correct and incorrect statements.

I. A catalyst increases the rate of a reaction.

II. All catalysts are solids.

III. The mass of a catalyst is the same before and after the reaction.

IV. A catalyst lowers the enthalpy change of a reaction, enabling more particles to have sufficient energy to successfully react.

V. A catalyst increases the value of the equilibrium constant, thus favouring the extent of the forward reaction, resulting in a greater yield of product.

VI. All catalysts align the reactant particles in an orientation that is favourable for a reaction to occur.

VII. The effectiveness of a metal catalyst is not dependent upon its surface area.

VIII. Enzymes are biological catalysts that catalyse a specific biochemical reaction once only.

IX. The effectiveness of an enzyme is independent of temperature.

a. Identify two correct statements. 1 MARK

b. Evaluate the student's summary by identifying three incorrect statements. In each case, explain why it is incorrect.

i. Incorrect statement one 2 MARKS

ii. Incorrect statement two 2 MARKS

iii. Incorrect statement three 2 MARKS

VCAA 2013 Exam 2 Short answer Q11

FROM LESSONS 4A, 4B & 5B

Chapter 11 review

Multiple choice (10 MARKS)

Question 1 (1 MARK)

Below are a number of statements regarding medicines.

I. No medicines approved for use in Australia are extracted from plants.

II. Medicines can work by stopping an enzyme from acting.

III. Repeating the distillation process decreases the purity of medicines.

IV. Competitive inhibitors enhance enzymes' usual catalytic activity.

Which of these statements is/are correct?

A. I, III, and IV only

B. II only

C. III only

D. II and IV only

Question 2 (1 MARK)

Which of the following is a correct statement about the process of protein denaturation?

A. High temperatures denature proteins by disrupting forces and bonds between polypeptide chains.

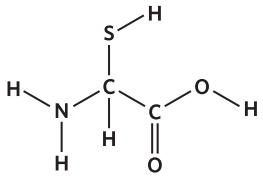
B. Changes in pH result in denaturation by disrupting the protein's primary structure.

C. Denaturation is a reversible process.

D. Denaturation involves the disruption of all forces and bonds in the protein's secondary, tertiary and quaternary structures.

Use the following information to answer questions 3–5.

Cysteine is one of the two amino acids that contain sulfur atoms. A scientist has developed a new medicine that selectively breaks the covalent bonds between two sulfur atoms of non-adjacent amino acids in a protein. The structure of cysteine is shown.



Question 3 (1 MARK)

The following is a diagram of a section of a protein chain.

The bonds/forces represented by X and Y are

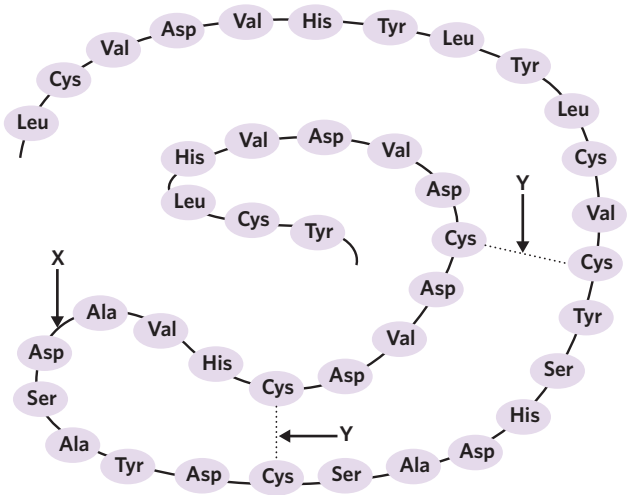
A. X: amide bond; Y: disulfide bond

B. X: covalent bond; Y: ionic bond

C. X: hydrogen bond; Y: peptide bond

D. X: dipole-dipole force; Y: covalent bond

Adapted from VCAA 2011 Exam 1 Multiple choice Q5



Question 4 (1 MARK)

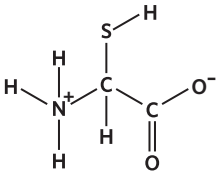
What level of protein structure would be most directly affected by the medicine?

A. Primary **B.** Secondary **C.** Tertiary **D.** Quaternary

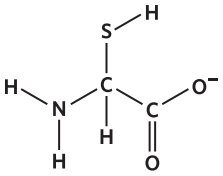
Question 5 (1 MARK)

The pH in the bloodstream is approximately neutral. Which of the following represents the structure of cysteine in the bloodstream?

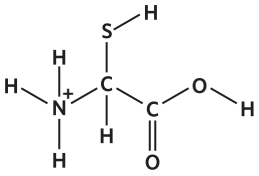
A.



B.



C.



D. Cysteine's structure would not change in a solution of neutral pH.

Question 6 (1 MARK)

Which of the following is true of amino acids?

A. In basic solutions, the amino group attached to the α-carbon exists in the $-NH_3^+$ form.

B. Amino acids only contain the elements C, H, O, and N.

C. In solutions of high pH, amino acids form zwitterions.

D. Amino acids are amphiprotic.

Question 7 (1 MARK)

The protein haemoglobin acts as an oxygen carrier in the bloodstream and consists of four subunits that form its complex quaternary structure. A student tested four separate samples of pure haemoglobin in the form of 1 M aqueous solutions.

In which of the following tests would the primary structure of haemoglobin most likely be disrupted?

A. Blend the solution at very high speed.

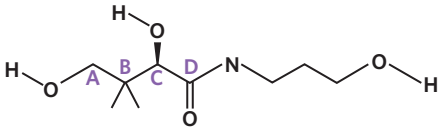
B. Warm the solution and test for gas(es) evolved.

C. Add concentrated hydrochloric acid to the solution then boil the solution.

D. Add methanol that will disrupt the hydrogen bonding in haemoglobin.

Use the following information to answer questions 8–9.

Panthenol is a compound which can be applied to the skin as a moisturiser. One of its two optical isomers, dexpanthenol (shown), has been shown to be an effective medicine for gastrointestinal conditions.



Question 8 (1 MARK)

Which of the following is a chiral centre?

A. Carbon atom A

B. Carbon atom B

C. Carbon atom C

D. Carbon atom D

Question 9 (1 MARK)

Which of the following best explains why dexpanthenol is separated from panthenol's other optical isomer when used as a gastrointestinal medicine?

A. Using a single optical isomer uses less energy, hence saving money for medicine manufacturers.

B. Dexpanthenol has more polar groups than its optical isomer, enabling it to dissolve better in the body.

C. Dexpanthenol's optical isomer may interact differently in the body and hence have different medicinal properties.

D. Dexpanthenol is achiral, whereas its optical isomer is chiral and more difficult to manufacture.

Question 10 (1 MARK)

A manufacturer wishes to extract salicin to make aspirin. To determine the best method, the manufacturer has access to the following table of data on organic compounds commonly present in plants.

Compound	Melting point (°C)	Boiling point (°C)	Solubility in hexane	Solubility in ethanol	Solubility in water
Salicin	207	240	low	moderate	high
Globulol	89	293	high	high	low
Verbenone	7	229	high	high	low
Oxalic acid	190	365	low	high	high

Based on the data in the table, which of the following extraction and purification methods would be most appropriate for separating salicin from verbenone?

A. Simple distillation

B. Steam distillation

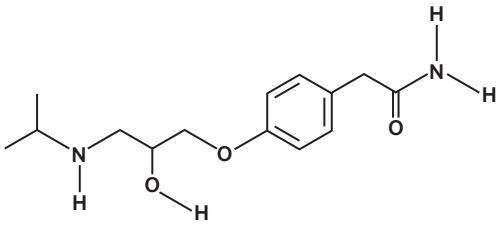
C. Solvent extraction using water and ethanol

D. Solvent extraction using water and hexane

Short answer (30 MARKS)

Question 11 (5 MARKS)

Atenolol is a medicine used to treat high blood pressure. It acts by dissolving in the (aqueous) bloodstream, then blocking receptors in the heart to decrease heart rate.



a. Describe what techniques a chemist could use to identify atenolol's:

i. Functional groups 1 MARK

ii. Structure 1 MARK

b. Considering atenolol's mode of action, why are polar functional groups necessary to its function? 1 MARK

c. The binding of medicines to receptors can be considered in terms of the lock-and-key model. Explain, according to this model, how atenolol blocks receptors in the heart. 2 MARKS

Question 12 (7 MARKS)

A protein's overall shape is maintained by intermolecular forces in its secondary, tertiary and quaternary structure.

a. Describe the different intermolecular forces and arrangements involved in a protein's secondary and tertiary structure. 4 MARKS

b. The protein transferrin is used as an iron carrier in the bloodstream. A sample of transferrin was isolated and then dissolved in a solution with a pH of 2.3. After a few minutes, significant 'clumps' were observed in the solution. Explain this observation. 3 MARKS

Question 13 (3 MARKS)

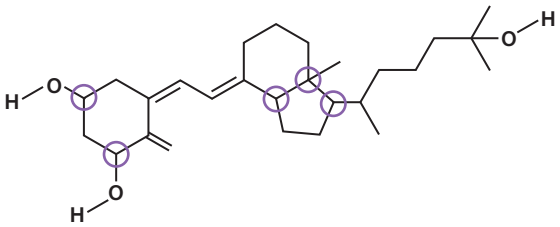
A chemist has designed a medicine that exists as a racemate (a 50/50 mixture of two optical isomers). In order for it to have the desired effect, the medicine needs to be able to be broken down by enzymes in the body. However, the chemist soon discovers that only half the medicine is broken down in the body. Using your knowledge of optical isomers and enzymes, suggest a reason why this might be the case.

Question 14 (3 MARKS)

Hyperthermia is a medical condition where the body's temperature exceeds the normal range and hypothermia is a medical condition where the body's temperature is below that of the normal range. With reference to enzyme activity and temperature, justify why doctors consider both of these conditions to be life-threatening.

Question 15 (10 MARKS)

The enzyme 24-hydroxylase catalyses the breakdown of the active form of vitamin D in the body. The structure of the active form of vitamin D is shown, with five of its six chiral centres circled.



a. Identify the sixth chiral centre. 1 MARK

b. Explain why this molecule is chiral. 2 MARKS

c. Explain why this enzyme would not break down a different optical isomer of vitamin D. 2 MARKS

d. With specific reference to the energy of the reactant molecules, describe how an enzyme catalyst acts to increase the rate of a chemical reaction. 3 MARKS

e. Describe the process of this enzyme catalysis, assuming 24-hydroxylase acts via the lock-and-key model. 2 MARKS

Question 16 (2 MARKS)

E. coli bacteria, which are made up of proteins (like enzymes), cause severe food poisoning when ingested. Explain one way you could minimise the risk of food poisoning from meat that contains *E. coli* bacteria.

Key science skills (10 MARKS)

Question 17 (5 MARKS)

Captopril is the earliest example of a competitive enzyme inhibitor used as a medicine primarily to treat high blood pressure. It acts by inhibiting an enzyme which converts angiotensin I to angiotensin II (a substance that increases blood pressure).

A major pharmaceutical company was seeking to market captopril as a treatment for numbness of fingers in cold weather. To test its effectiveness while saving on costs, they tested the medication on 30 company employees, of whom 17 reported a reduction in numbness of their fingers when using the medication.

a. Scientists often use models to communicate chemical ideas. Using the lock-and-key model, draw diagrams to represent this enzyme's usual action, and how captopril acts to inhibit it. 3 MARKS

b. Evaluate the validity of this study, based on the excerpt given. 2 MARKS

FROM LESSONS 12D & 12E

Question 18 (5 MARKS)

Every year, thousands of medicines reach the trial phase, yet in Australia, only around 40 medicines are approved for use annually.

a. Explain why it is particularly difficult to approve the safety and effectiveness of chiral medicines. 2 MARKS

b. Describe one factor relevant to the approval of medicines under each of the following themes:

i. Social 1 MARK

ii. Legal 1 MARK

iii. Economic 1 MARK

FROM LESSON 12B

Back to contents

UNIT 4 AOS 3

How is scientific inquiry used to investigate the sustainable production of energy and/or materials?

Students undertake a student-designed scientific investigation in either Unit 3 or Unit 4, or across both Units 3 and 4. The investigation involves the generation of primary data related to the production of energy and/or chemicals and/or the analysis or synthesis of organic compounds, and should be inspired by a contemporary chemical challenge or issue. The investigation draws on knowledge and related key science skills developed across Units 3 and 4 and is undertaken by students in the laboratory and/or in the field.

When undertaking the investigation students are required to apply the key science skills to develop a question, state an aim, formulate a hypothesis and plan a course of action to answer the question, while complying with safety and ethical guidelines. Students then undertake an experiment to generate primary quantitative data, analyse and evaluate the data, identify limitations of data and methods, link experimental results to scientific ideas, discuss implications of the results, and draw a conclusion in response to the question. The presentation format for the investigation is a scientific poster constructed according to the structure outlined in the study design. A logbook is maintained by students for recording, assessment and authentication purposes.

Outcome 3

On completion of this unit the student should be able to design and conduct a scientific investigation related to the production of energy and/or chemicals and/or the analysis or synthesis of organic compounds, and present an aim, methodology and method, results, discussion and conclusion in a scientific poster.

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12

CHAPTER 12
Scientific Investigation

LESSONS

12A Scientific research
12B Conducting an experiment
12C Interpreting data
12D Experimental factors affecting data
12E Writing scientific material
Chapter 12 review

KEY KNOWLEDGE

Investigation design

- chemical concepts specific to the selected scientific investigation and their significance, including definitions of key terms
- characteristics of the selected scientific methodology and method, and appropriateness of the use of independent, dependent and controlled variables in the selected scientific investigation
- techniques of primary quantitative data generation relevant to the selected scientific investigation
- the accuracy, precision, repeatability, reproducibility, resolution and validity of measurements
- the health, safety and ethical guidelines relevant to the selected scientific investigation

Scientific evidence

- the nature of evidence that supports or refutes a hypothesis, model or theory
- ways of organising, analysing and evaluating primary data to identify patterns and relationships, including sources of error and uncertainty
- authentication of generated primary data through the use of a logbook
- assumptions and limitations of investigation methodology and/or data generation and/or analysis methods

Science communication

- conventions of science communication: scientific terminology and representations, symbols, formulas, standard abbreviations and units of measurement
- conventions of scientific poster presentation, including succinct communication of the selected scientific investigation, and acknowledgements and references
- the key findings and implications of the selected scientific investigation

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12A Scientific research

STUDY DESIGN DOT POINTS

- the nature of evidence that supports or refutes a hypothesis, model or theory
- chemical concepts specific to the selected scientific investigation and their significance, including definitions of key terms
- characteristics of the selected scientific methodology and method, and appropriateness of the use of independent, dependent and controlled variables in the selected scientific investigation

12A 12B 12C 12D 12E

4.3.1.1 Scientific vs non-scientific ideas

4.3.2.1 Linking chemical concepts to investigations

ESSENTIAL PRIOR KNOWLEDGE

- Variables

See questions 96.



Image: Blue Planet Studio/Shutterstock.com

What makes something 'scientific'?

Although we have gained a lot of knowledge over time, only some of that knowledge is considered scientific. Throughout history, humans have been able to gain a lot of knowledge about the world and about ourselves. In early history, discoveries and knowledge were passed on to generations through different methods such as storytelling, dancing, and artefacts. Some of the early knowledge was gained through experiences, intuition, and the senses. In this lesson, we will learn about the development of **scientific ideas**.

KEY TERMS AND DEFINITIONS

Aim purpose of an experiment
Controlled variable(s) variable(s) held constant throughout the experiment
Dependent variable variable that is measured by the experimenter
Hypothesis testable statement which predicts the outcome of an experiment
Independent variable variable that is deliberately manipulated by the experimenter
Non-scientific ideas ideas that are not developed by following a scientific method
Primary source source providing original data, written by the experimenter
Scientific ideas ideas that are developed by following a scientific method
Scientific method procedure used to investigate scientific ideas
Secondary source source that has interpreted primary sources
Variable any factor (e.g., substance, condition, property) that is capable of changing throughout an experiment

Scientific vs non-scientific ideas 4.3.1.1

Over time, we have developed a systematic process of developing and explaining new knowledge: a process referred to as the **scientific method** (figure 1).

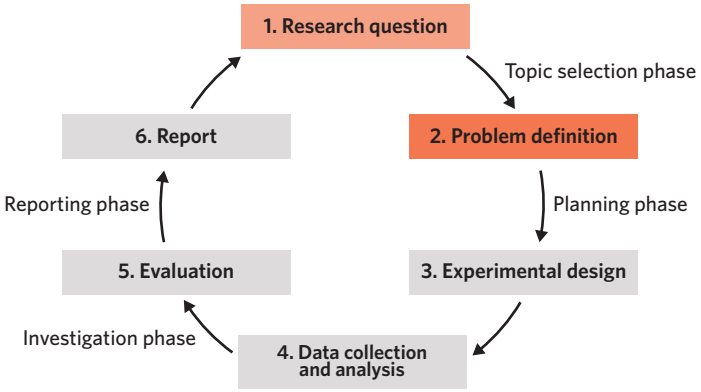


Figure 1 A scientific method

How is science conducted?

A scientific method involves predictions, conducting experiments to collect relevant evidence, making conclusions based on that evidence, and ultimately improving knowledge.

The ideas that are developed using a scientific method are known as **scientific ideas**. The theories that we will study throughout this course have been developed through this process, and can therefore be considered scientific ideas.

Scientific ideas are usually presented in the format shown in figure 2.

This general structure is followed by scientists who conduct research and is how many scientific journal articles are presented. Developments in scientific knowledge are published in journals and are checked by other scientists to ensure that the right processes have been followed and that the conclusions are valid (this process is called 'peer review').

Ultimately the knowledge gained as a result of the execution of a scientific method contributes to our understanding of the world, as shown in figure 3.

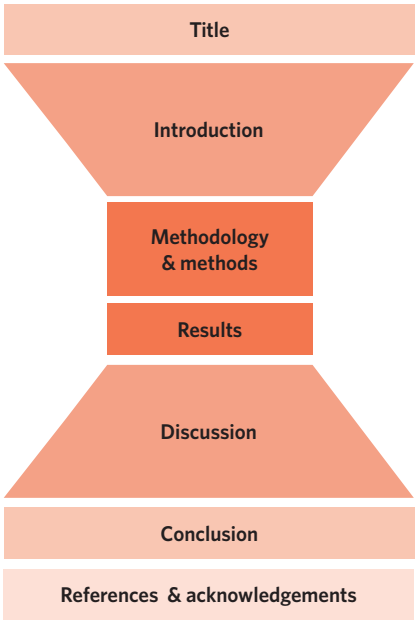


Figure 2 General format used when presenting scientific ideas

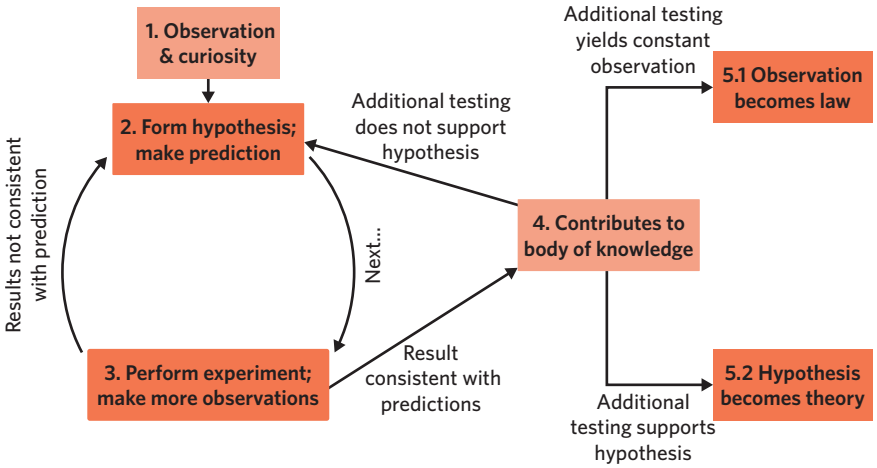


Figure 3 The development of scientific knowledge

There are some ideas that are difficult to measure and have not necessarily been developed using the scientific method. We call these ideas **non-scientific ideas**. For example, ideas developed through personal experience or tradition that have not been examined are considered non-scientific.

PROGRESS QUESTIONS

Question 1

Which of the following statements is correct?

A. Scientific ideas are purely developed through past experiences.

B. Scientific ideas do not have to be testable.

C. Scientific ideas should contribute knowledge to society.

D. Scientific ideas only need to be proven once.

Question 2

"Art is in the eye of the beholder, and everyone will have their own interpretation." – E.A. Bucchianeri.

Art interpretations are

A. scientific ideas.

B. non-scientific ideas.

C. testable.

D. developed via the scientific method.

Question 3

The results of a 'scientific' experiment

A. must always be the same as the results of previous studies.

B. may differ from previous findings.

C. do not need to be reproducible by another researcher.

D. do not need to be supported by evidence.

Linking chemical concepts to investigations 4.3.2.1

Scientific knowledge is built upon previous ideas; our knowledge of chemistry today is a result of all of the knowledge that has previously been developed. The discoveries that we make now build upon this knowledge. Therefore, when choosing a research investigation, we need to acknowledge this by linking it to relevant chemical concepts. In doing so, we can ensure that the basis of our research stems from a solid theoretical foundation.

Why is brainstorming before an investigation important?

When brainstorming ideas about a potential scientific investigation to pursue, it's useful to choose an area of interest and then conduct background research into what has been already established in the area. Most of the time, this involves finding journal articles of previous research that have investigated questions in the same area/field. In doing so, we are able to gain a better understanding of the current situation, and it also helps to give direction to the kind of research that we can conduct.

For example, say we were interested in investigating water quality. Due to the fact that water is a very important resource, we need to ensure that our water is of appropriate quality for the many different functions in our daily lives. As a result, we need to conduct regular tests to ensure that our water is not contaminated with harmful chemicals and that it has low levels of heavy metals and salts. Figure 4 shows how a research idea can be developed.

USEFUL TIP

Throughout chapter 12 you will see the blue bottle icons which are all part of an ongoing investigation that comes together as a 600 word poster in lesson 12E.

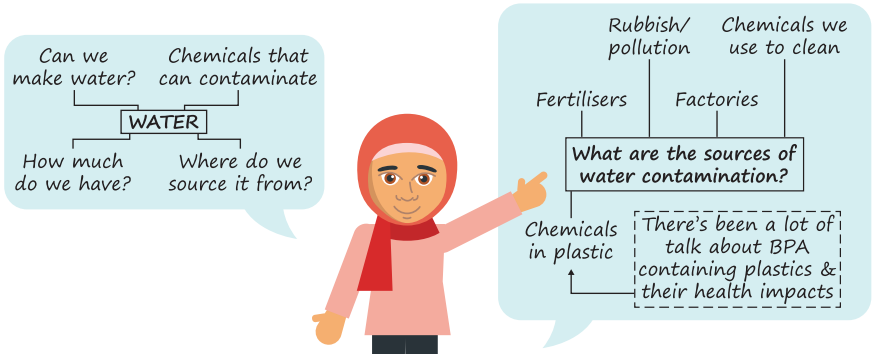


Figure 4 Brainstorming of potential research topics

From this, we can start researching the area to find out more about what is currently understood about the topic, as shown in figure 5.

The best place to gather information about the chemical theory related to different concepts is through reading journal articles and literature reviews related to the topic of interest. These can be original research articles which contain the experimental data and are referred to as **primary sources**, or other resources such as articles or books that have already reviewed and summarised the data, which are referred to as **secondary sources**. These types of articles provide a broad overview of the related theory and include related research that can be further explored depending on the specific area of interest. This step is particularly important as it provides us with:

- Relevant terminology and definitions that we will need to use throughout the investigation.
- Underlying chemical concepts related to the research.
- Possible methods that can be adapted to our own research.

During this process, it is important to make sure that we use resources that have come from reputable sources to ensure that the information is accurate. This involves considering questions such as:

- Who wrote the article?
  - Are they an expert in the field?
- Where was the article published?
  - Was the article published in a peer-reviewed journal?
- Does the author have affiliations with the relevant industry?
  - Have they been funded by a private company in the industry?

BPA SCIENTIFIC INQUIRY



In this example, we should be conducting research to find out more about BPA

BPA research:
- Is short for Bisphenol A.
- Used to make plastics (a polymer)
- Several studies identified that BPA is harmful to our health.
- Most studies have used HPLC as the analytical technique to analyse the levels of BPA.

Figure 5 Researching BPA.

How do we review scientific research?

Most scientific research is presented in the format outlined in figure 2. When reviewing the research, there are some key features that we need to consider.

Although we can get a general overview of the theory and purpose of the study from the introduction, the more important sections of scientific research are the results and methods. By interpreting the data presented in the results section, we are able to further understand the theory being tested. The results section may support the theory by highlighting an expected relationship, or it may question the theory by showing results that do not match the current theoretical understanding. It is important that we are able to evaluate the methodology of the experiment to see whether or not errors may have affected the results, especially in situations where the results deviate from the theory. When reviewing the methodology, we need to ask questions like:

- Is this method appropriate for what we are trying to find?
- Are there any potential errors that may occur during the process?
- How has the data been analysed and interpreted?
- Are there other possible interpretations?

By doing so, we can be more confident with our analysis of the research.

How can we develop a scientific investigation?

Once we have a clearer understanding of the topic, we are able to further refine the research question and begin to develop the scope of the research investigation, as well as write the introduction section of our investigation.

BPA SCIENTIFIC INQUIRY



Is it dangerous to drink water from a plastic water bottle that has been left in a warm environment?

Introduction

Bisphenol A (BPA), shown in figure 6, is a monomer used to produce a strong plastic polymer known as polycarbonate. Originally developed for medical uses, BPA is now used to produce strong plastics found in everyday products such as bottles, food containers, and pipes. Due to its widespread use, there is growing concern over the health effects of using BPA.

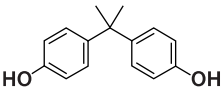


Figure 6 Structure of a bisphenol A (BPA) monomer

In water-containing products, BPA is known to leach into the water over time (Le et al, 2008). When consumed, this can result in the disruption of hormone-driven processes in the body (Diamanti-Kandarakis et al, 2009). This is potentially dangerous as there are many reactions in the body that are driven by hormones.

In order to be released into the water, BPA needs to be hydrolysed. Due to this, factors such as heat, pH conditions, and microwaves can all affect the extent to which BPA is released into its surrounding environment.

Aim

This experiment aims to test the effect of heat on the release of BPA into water.

Hypothesis

If the breakdown of BPA from plastic depends on the heat of the surrounding environment, then an increase in temperature would result in an increase in the concentration of BPA found in the water.

As we can see based on our example experiment, it is important to ensure that our research is based on and linked to theoretical concepts. Although these links are first introduced here, the chemical ideas need to be woven throughout the whole research investigation. Understanding the underlying scientific theory not only helps us to develop an **aim** and **hypothesis** for the investigation, it also helps us to explain the results of the experiment.

While the aim of an experiment is a statement about the purpose of the research, the hypothesis describes what we expect to happen as a result of the experiment. To develop the hypothesis we first need to understand the main **variables** in the experiment. More specifically, we need to be able to identify the variable that is being manipulated by the experimenter, the **independent variable**, and the variable that is affected by the change and thus measured, the **dependent variable**. We can then develop a hypothesis that proposes how the independent variable will affect the dependent variable. All variables that should be kept consistent throughout the whole experiment are known as **controlled variables**.

A simple way to develop a hypothesis can be seen in table 1.

Table 1 Framework for developing a hypothesis (IV: independent variable, DV: dependent variable)

If ...	**Phrase outlining relationship between DV and IV**	**then ...**	**Trend indicating effect on the DV**	**when ...**	**Trend indicating action by the IV**
	... depends on ...		... show an increase/decrease ...		... increased/decreased...
	... results from ...		... be greater than/less than ...		... greater/less ...
	... is affected by ...		... be larger than/smaller...		... large/small ...
	... is directly related to...				

PROGRESS QUESTIONS

Question 4

The order in which the following tabs should be placed in order to align with a scientific method is

I. Aim: to determine whether atoms have a mass in the centre of their structure.

II. It can be concluded that atoms have a mass in the centre of their structure.

III. Based on the results, it can be seen that…

IV. 1. Set up the cathode ray.
2. Place two charged plates around the cathode ray.

A. I, III, IV, II.

B. I, IV, III, II.

C. III, I, VI, II.

D. IV, I, II, III.

Question 5

Which of the following is a primary source?

A. Edrolo VCE chemistry textbook

B. Review article summarising previous work in the field

C. Popular science podcast

D. Research article in a scientific peer–reviewed journal

Question 6

When analysing a scientific article, why is it important to consider who wrote the article?

A. The author may be biased.

B. The author may not have sufficient expertise.

C. The author's background may influence their interpretation of results.

D. All of the above

Question 7

The hypothesis should explicitly relate the

A. controlled variables and the independent variable.

B. aim and the background information.

C. controlled variables and the dependent variable.

D. dependent variable and independent variable.

Question 8

The observations made during an experiment should be attributable to changes in

A. the controlled variables.

B. the controlled variables and the independent variable.

C. the independent variable.

D. the independent variables.

Theory summary

- Scientific ideas are ideas that have been developed through experimentation following a scientific method.
- Non-scientific ideas are ideas that have not been developed as a result of a scientific method.
- Research needs to be conducted prior to an investigation to identify current knowledge within the field of interest.
- The aim and hypothesis identify the purpose and prediction of the research respectively.
- Variables are elements of an experiment that can be changed, controlled or measured.

12A Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 9–11.

The composition of eggshells is very similar to the enamel found on teeth. Col wanted to conduct an experiment to identify factors that may contribute to the breakdown of tooth enamel.

Below is a short excerpt of the experimental write-up:

Materials

- Eggshells
- Cola
- Lemon juice
- Milk
- Timer
- Four beakers

Method

1. Label four beakers from A to D.
2. Place a 1 cm piece of eggshell in each beaker.
3. In beaker A, add 20 mL of cola.
4. In beaker B, add 20 mL of lemon juice.
5. In beaker C, add 20 mL of milk.
6. In beaker D, add 20 mL of water.
7. Leave the experiment for 2 hours.
8. Make observations and record results.

Question 9 (1 MARK)

The main difference between beakers A to D is the

A. volume of substance added.
B. type of liquid used.
C. amount of eggshell used.
D. length of time of the experiment.

Question 10 (1 MARK)

The variable(s) that should be kept constant in this experiment are the

I. volume of substance added.
II. type of liquid used.
III. amount of eggshell used.
IV. duration of the experiment.

A. I only
B. I & II
C. I & III
D. I, III & IV

Question 11 (2 MARKS)

Identify the dependent and independent variables in the experiment.

Exam-style

Question 12 (1 MARK)

The aim from a student's experimental report is shown below.

'To investigate how the oxidation rate of ethanol in white wine from a freshly opened bottle is affected by the concentration of ethanol in the wine'

What is the independent variable in this experiment?

A. The oxidation rate of ethanol

B. The type of wine

C. The temperature of the room

D. The concentration of ethanol in the wine

Adapted from VCAA 2022 exam Short answer Q8c

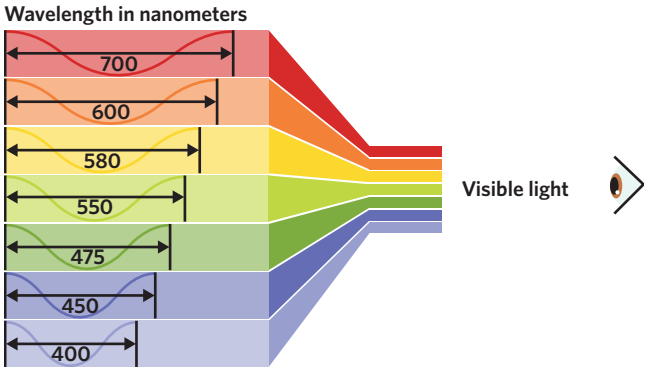
Question 13 (2 MARKS)

It's not quite known where Zodiac signs originated from, however, it is believed that people used to refer to the movement of the sun and stars to predict the future. This eventually led to the development of the zodiac signs, each of which was based on the interaction between constellations and their placement between the sky and the sun during certain periods. Nowadays, many people look to these signs to help them explain current and/or future events. What type of idea would this be considered as? Explain.

Question 14 (3 MARKS)

Bug zappers use visible light to attract bugs.

Edwin wanted to determine which wavelength of the visible light spectrum would be most effective in attracting bugs. The wavelengths of each colour in the visible light spectrum are shown.



a. Identify the independent variable for this experiment. 1 MARK

b. Write an appropriate hypothesis for this experiment. 2 MARKS

Question 15 (1 MARK)

A student hypothesised that polishing the zinc, Zn, electrode in an Fe-Zn galvanic cell would increase the current produced by the cell.

What would be the **most** valid method of testing this hypothesis?

A. Researching the scientific literature to determine how polishing changes the structure of Zn

B. Measuring the conductivity of a Zn electrode after polishing it

C. Measuring the change in mass per unit time of the Fe electrode in the same Fe-Zn galvanic cell before and after the Zn electrode was polished

D. Measuring the current produced by two different Fe-Zn galvanic cells, one using a polished Zn electrode and the other using an unpolished Zn electrode

VCAA 2021 exam Multiple choice Q10

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12B Conducting an experiment

STUDY DESIGN DOT POINTS

- techniques of primary quantitative data generation relevant to the selected scientific investigation
- the health, safety and ethical guidelines relevant to the selected scientific investigation

12A 12B 12C 12D 12E

- 4.3.3.1 Qualitative data collection
- 4.3.3.2 Quantitative data collection
- 4.3.4.1 Social, legal, political and economic influences
- 4.3.5.1 & 4.3.5.2 Ethical considerations & safety guidelines

ESSENTIAL PRIOR KNOWLEDGE

- Quantitative vs qualitative data

See question 97.

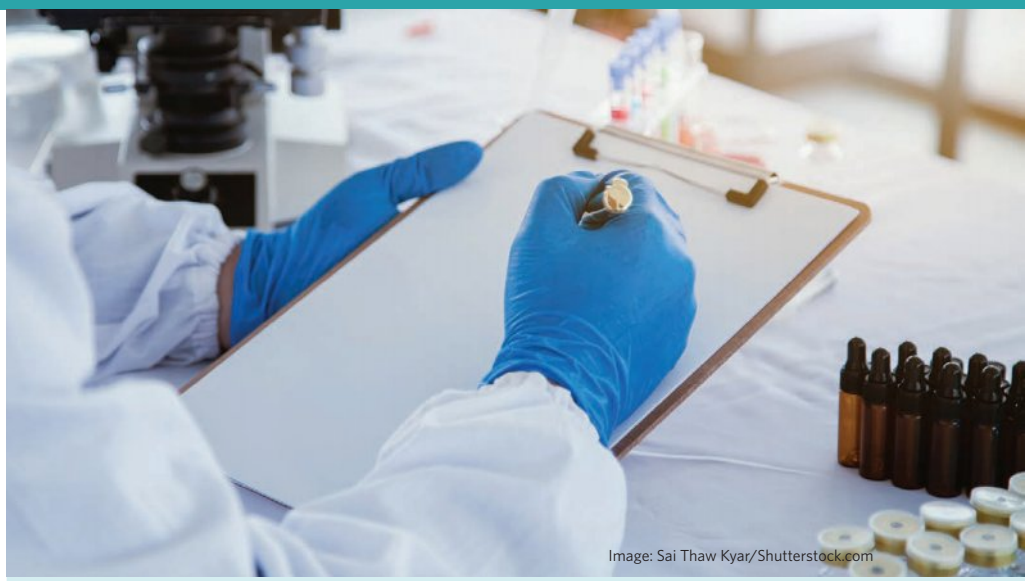


Image: Sai Thaw Kyar/Shutterstock.com

How important is experimental design?

In this lesson, we will be learning about the factors that we need to take into consideration when selecting and conducting an experiment.

KEY TERMS AND DEFINITIONS

Economic considerations taking into account the associated costs of time and money

Ethical considerations taking into account the effect on other living organisms (e.g. humans and animals)

Legal considerations taking into account the legality of research, as well as how the research may influence the law

Political considerations taking into account current governmental policies, and the political environment of society more broadly

Primary data original data collected firsthand by researchers

Qualitative analysis technique that determines a non-numerical result

Qualitative data non-numerical (descriptive) data collected based on observations taken during an experiment

Quantitative analysis technique that identifies the amount of substance present

Quantitative data numerical data collected during experiments

Safety Data Sheet (SDS) document that outlines the health and safety information associated with different materials and chemicals

Secondary data data that has been previously collected that is now accessible to different researchers

Social considerations taking into account the effect on society

Qualitative data collection 4.3.3.1

Different experiments can produce different types of data, which means that researchers can select the most appropriate experimental method for their topic of investigation (figure 1). Broadly speaking, the types of data usually obtained from chemistry experiments can be broken down into two categories: **qualitative data** and **quantitative data**.

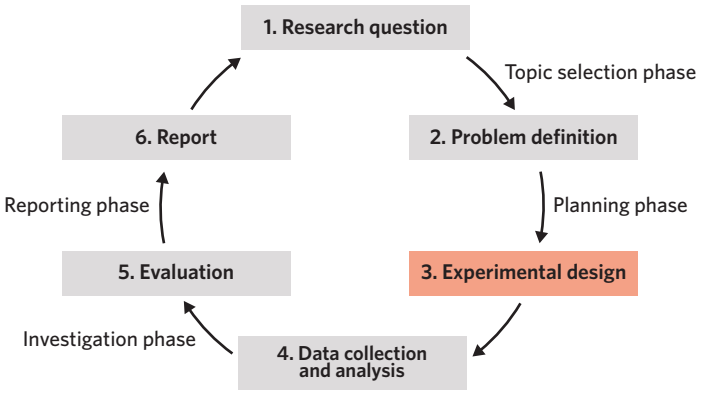


Figure 1 A scientific method

How can qualitative scientific data be collected?

One of the main ways in which we can continue to develop scientific theory is through conducting experiments to obtain data, which is then used to develop conclusions about the area of study. The data that is evaluated can either have been collected by the original experimenters, known as **primary data**, or collected indirectly from other experiments, referred to as **secondary data**.

USEFUL TIP

Primary data = 'firsthand'
Secondary data = 'secondhand'

When we first started exploring chemistry, a lot of the data obtained from experiments is based on observations made during reactions. Colour changes, odours and changes of physical state are all examples of the types of data that may be collected. This type of data is classified as qualitative data. Qualitative data is based on observations that are then used to interpret what has occurred as a result of a reaction. This **qualitative analysis** allows us to gain information about what substances are made of.

An example of a technique that can gather some qualitative data that will be studied in the course is acid-base titration. One component of acid-base titrations involves observing a colour change, which signifies the point at which the experiment should stop, as shown in figure 2. The advantage of collecting this type of data is that it can give a quick indication as to whether or not a reaction has taken place. Table 1 shows examples of qualitative data collected from different reactions.

Table 1 Qualitative data collected from different reactions

Reaction	Example of qualitative data collected
Acid-base titrations	Colour change
Precipitation reactions	Formation of a solid
Esterification	Fruity odour



Image: NamPu NiNu/Shutterstock.com

Figure 2 Colour changes are a common example of qualitative data.

PROGRESS QUESTIONS

Question 1

Qualitative analysis is most applicable when an experimenter requires information about

A. colour differences.
B. temperature changes.
C. mass changes.
D. conductivity changes.

Question 2

The following image shows the collection of

A. primary qualitative data.
B. primary quantitative data.
C. secondary quantitative data.
D. secondary quantitative data.



Image: Ajamal/Shutterstock.com

Quantitative data collection 4.3.3.2

Many experiments provide numerical, quantitative data.

How can numerical scientific data be collected?

Unlike qualitative data, quantitative data is expressed numerically and can be used to calculate the amount of a substance. This type of data is important as it can help us determine the amount of a substance that is needed for a desired reaction, and also helps us to predict the products that can be formed. Quantitative data is obtained through **quantitative analysis**. Examples of quantitative analytical techniques that are studied in the course include solubility analysis, gravimetric analysis, acid-base titrations and chromatography (figure 3) . These techniques are summarised in table 2.

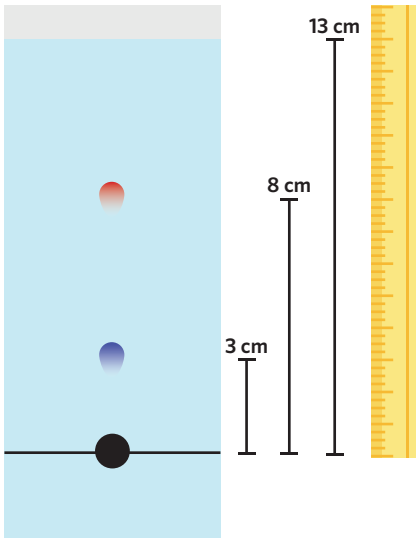


Figure 3 Numerical data can be produced using paper chromatography

Table 2 Quantitative data collected from different techniques

Technique	Example of quantitative data collected
Solubility analysis	Mass of solute dissolved in a known volume of solvent
Gravimetric analysis	Mass of precipitate formed
Acid-base titrations	Concentration of unknown sample
Chromatography	Distance moved by different components

USEFUL TIP

Quantitative data will often have a unit of measurement e.g. mass in g, solubility in g mL^{-1}, and concentration in mol L^{-1}.

When selecting an appropriate technique for an experiment, it is important to understand the type of data that is required to answer the research question. If we pick a technique that is inappropriate for the investigation, the results may not address the research question, jeopardising the validity of the experiment. We will learn about the concept of validity in greater depth in the following lessons.

PROGRESS QUESTIONS

Question 3

This image represents the collection of

A. primary qualitative data.
B. primary quantitative data.
C. secondary qualitative data.
D. secondary quantitative data.



Image: ggw/Shutterstock.com

Continues →

Question 4

Secondary data

A. can be quantitative only.

B. is neither quantitative nor qualitative.

C. can be qualitative only.

D. can be quantitative or qualitative.

Social, legal, political and economic influences 4.3.4.1

Scientific research has wide-reaching implications outside the scientific community.

How can scientific research affect society?

Regardless of the type of experiment conducted, when designing a research investigation, we need to ensure we consider the wider implications of the study. Questions that could be asked during this process include:

- Who will be impacted by the results of the study?
- How will the results of the study contribute to the decision-making process of a governing political party?
- What are the implications of the study with respect to the law?

Although it may seem like the experiment we conduct may not have a large impact on the wider community, the social, economic, legal and political decisions that are made today are informed by the momentous amount of work that has previously been done by scientific researchers. For example, the different strategies and agreements that have been developed to reduce our impact on the environment come from the countless studies that have been conducted in all fields of science. When conducting research, we need to think about the:

- **Social considerations** – who is being affected by the research?
- **Economic considerations** – what are the associated monetary and resourcing costs?
- **Legal considerations** – how is the research affected by the law?
- **Political considerations** – do any governing bodies have an influence on the research?

The results from scientific research have flow-on effects that can impact many people and industries in different ways. Figure 4 shows an example of the potential effects of scientific research around dichlorodiphenyltrichloroethane (DDT), a chemical that was used as an insecticide.

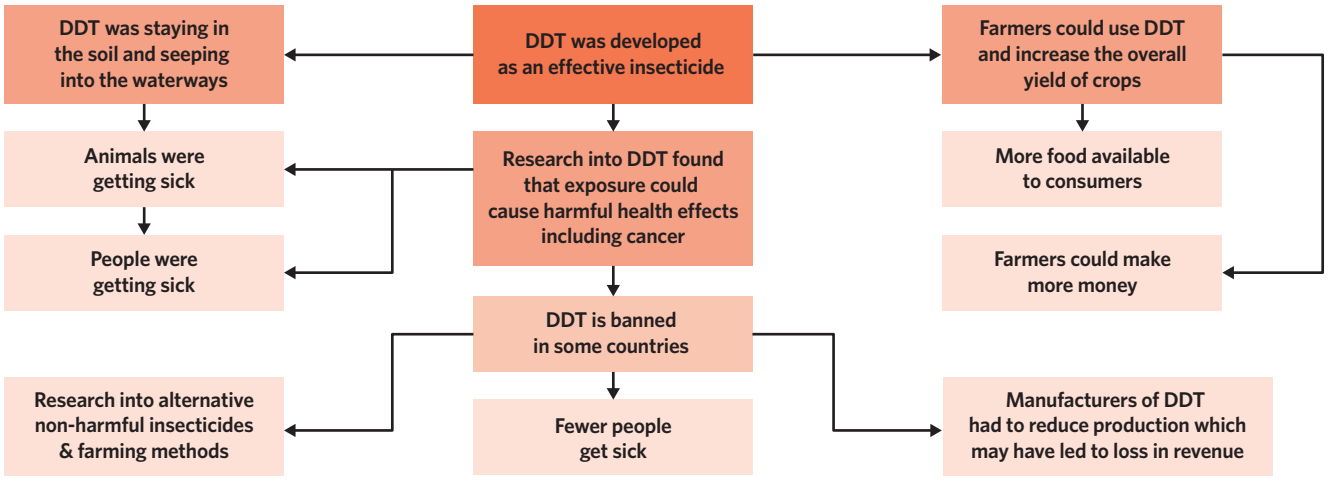


Figure 4 Illustration of potential impacts of scientific research

PROGRESS QUESTIONS

Question 5

All scientific research findings

A. have positive implications for all areas of society.

B. will have critical social, economic, legal and political considerations.

C. are built on previous scientific findings.

D. are ethical and appropriate, as long as they are legal.

Question 6

The following statement was made by a hospital in response to a new specialised gene therapy they had been trialling:

"Although obviously effective, the therapy is too complicated and takes too long to administer. We cannot afford the salaries of the extra staff that would be required."

This is an example of a(n)

A. social consideration.

B. economic consideration.

C. legal consideration.

D. political consideration.

Ethical considerations & safety guidelines 4.3.5.1 & 4.3.5.2

Ethics and safety guidelines should always be taken into account when conducting scientific research.

How do ethics influence scientific research?

Conducting scientific research is about more than just scientific theory. Due to the potential implications of the work, we are all responsible for the appropriate conduct and use of the knowledge obtained. As such, we need to make sure that we adhere to **ethical considerations** when conducting research. In other words, we need to make sure that we're trying our best to do the 'right' thing from a moral and principled perspective.

When thinking about all of the ethical issues that may arise from chemistry-related studies, we can categorise them into two main areas: the internal and external domains. The internal domain consists mainly of the issues related to the experiment itself whereas the external domain consists of the wider societal implications of the research. Table 3 shows examples of the two types of ethical domains.

Table 3 Examples of ethical issues in internal and external domains.

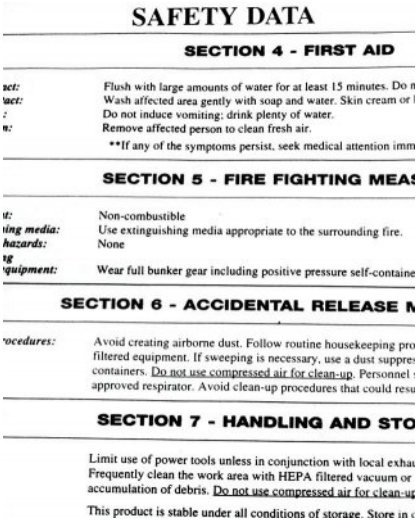
Internal domain	External domain
• Conducting experiments safely • Plagiarism • Data falsification • Acknowledgement of previous research (i.e. citations) • Animal/human testing	• Development of new substances • Environmental impacts • Societal impacts

Due to the importance of ethics in chemistry research, scientists met to develop a document known as the Hague Ethical Guidelines. This guideline outlines the main principles that we should try to abide by when conducting chemical research. This document is not directly related to the VCAA study design, but is a good resource that gives further information about ethics in chemistry.

Why is it important to protect the safety of everyone involved in scientific investigations?

All scientific experiments come with their own safety risks. There are many different types of risks, which vary depending on the type of experiment conducted. These risks can arise through the use of certain substances as well as from the experimental procedure itself.

Prior to conducting any experiment, it is important that the experimenter undertakes a thorough risk assessment and refers to the **Safety Data Sheet (SDS)** of all of the substances that will be used as part of the experiment. The SDS contains all of the health and safety information relating to materials/substances that will be used, including strategies and guidelines to help mitigate the effects of each. Figure 5 shows sections that are often included in an SDS.


SAFETY DATA

SECTION 4 - FIRST AID

Flush with large amounts of water for at least 15 minutes. Do n
Wash affected area gently with soap and water. Skin cream or l
Do not induce vomiting; drink plenty of water.
Remove affected person to clean fresh air.
**If any of the symptoms persist, seek medical attention imm

SECTION 5 - FIRE FIGHTING MEAS

Non-combustible
Use extinguishing media appropriate to the surrounding fire.
None
Wear full bunker gear including positive pressure self-containe

SECTION 6 - ACCIDENTAL RELEASE M

Avoid creating airborne dust. Follow routine housekeeping pro
filtered equipment. If sweeping is necessary, use a dust suppre
containers. Do not use compressed air for clean-up. Personnel
approved respirator. Avoid clean-up procedures that could resu

SECTION 7 - HANDLING AND STO

Limit use of power tools unless in conjunction with local exhau
Frequently clean the work area with HEPA filtered vacuum or
accumulation of debris. Do not use compressed air for clean-up
This product is stable under all conditions of storage. Store in

Figure 5 Sample SDS of a chemical substance

As part of the experimental process, scientists use an SDS to develop a risk assessment for the experiment to analyse the potential risks and outline specific strategies to minimise them. For example, experiments that result in the production of a potentially harmful gas would be required to be conducted in a fume hood. Other examples of safety measures that can be taken during an experiment include:

- Wearing protective equipment e.g. lab coat, safety glasses, etc.
- Knowing where the safety showers are and how to use them.
- Proper disposal of chemical waste.

For an experiment, we need to collate all of the information related to the substances that will be used in the experiment and develop a plan to minimise safety risks. This should be included as part of the 'Methodology and Methods' section of a scientific investigation.

PROGRESS QUESTIONS

Question 7

Identify the correct ethical statement.

A. Scientists who conduct research in the same area are able to use each other's findings without needing to acknowledge the source.

B. When a new substance or scientific technique is developed, it should be shared with the world.

C. Scientists do need to conduct a primary test of all the substances they are going to use before performing their actual experiment in order to find out the potential risks of using the substances.

D. Safety considerations for experiments only need to be documented after the experiment has been conducted, and only if issues arise during the experiments.

Theory summary

- Qualitative data is mainly observational.
- Quantitative data gives us numerical information about substances.
- Scientific findings can have social, legal and/or political, and economic implications.
- There are many ethical concerns related to chemical investigations that should be considered by the people conducting the research.
- It is very important to make sure that scientists are well informed about the nature of the experiment they are conducting so that they can put strategies in place to minimise the potential risks.

12B Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 8–10

When increasing atmospheric concentrations of carbon dioxide (CO_2) are discussed in the context of climate change, a silver lining is often postulated: "CO_2 is plant food." That is, higher concentrations of CO_2 are generally acknowledged to stimulate plant photosynthesis and growth, with potential benefits for the productivity of the cereal crops that remain the world's most important sources of food. Cereal crops feed not just humans but also the animals that are important sources of protein for many. Since the mid-1960s, cereal production increased by approximately a billion tons, yet accelerated progress in agriculture is needed to keep pace with population growth anticipated to reach between 9–10 billion by 2050, and to achieve Sustainable Development Goal (SDG) 2 to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture.

But food security is about more than just production. While increases in CO_2 may make some crops grow more quickly, research shows that higher CO_2 concentrations can also reduce the nutritional quality of staple crops, from potatoes to barley, rice to wheat.

https://journals.plos.org/plosmedicine/article?id=10.1371/journal.pmed.1002600

Citation: Ebi, K. L., & Ziska, L. H. (2018). Increases in atmospheric carbon dioxide: Anticipated negative effects on food quality. PLoS medicine, 15(7), e1002600. https://doi.org/10.1371/journal.pmed.1002600

Question 8 (1 MARK)

The effect of the CO_2 increase can be experienced by

A. direct consumers.

B. farmers.

C. food manufacturers.

D. all of the above.

Question 9 (1 MARK)

What effect would an increase in CO_2 have on the health of consumers?

A. Consumers will be able to eat less to obtain the same amount of nutrients.

B. Consumers will have to eat more to obtain the same amount of nutrients.

C. Consumers will spend less on food.

D. Consumers will eat less cereal.

Question 10 (3 MARKS)

Describe an economic issue evident in the passage.

Exam-style

Question 11 (1 MARK)

Ethoxyethane, $C_2H_5OC_2H_5$, is commonly used as a solvent in the purification of compounds. The boiling point of $C_2H_5OC_2H_5$ is 36 °C. The safety data sheet for $C_2H_5OC_2H_5$ states: 'Extremely flammable. Keep away from sources of ignition.'

During the purification process, a compound is dissolved in $C_2H_5OC_2H_5$ by heating it for an extended period of time. This is done using glassware that is open to the atmosphere. This step in the purification process should be carried out using a

A. water bath in a fume cupboard.

B. water bath on a laboratory bench.

C. Bunsen burner in a fume cupboard.

D. Bunsen burner on a laboratory bench.

Adapted from 2018 VCAA exam Multiple choice Q6

Question 12 (2 MARKS)

Ivaana and her team were conducting experiments to develop a new type of drug targeted at supporting patients with diabetes. As part of their work, they conducted extensive research on diabetes and the current available therapies and came across a study that was similar to theirs. The team used the results of the study to direct their research.

a. What type of data, primary or secondary, was Ivaana and her team collecting to do this research? 1 MARK

b. In an effort to finish the research on time, Ivaana copied and pasted the research conducted by the other team and used it as her own. What is the main ethical issue around what she did? 1 MARK

Question 13 (5 MARKS)

Luis was given two unknown samples of metallic substances and asked to determine the name of each. In his experience, he knew that he could use the flame test to differentiate between the two metallic substances. Upon conducting the experiment, Luis noticed that each sample gave off a different coloured flame.

a. Identify whether this type of analysis is qualitative or quantitative. 1 MARK

b. Luis wanted to use the results of the test to find how much of each substance was present. Is it possible for Luis to calculate the amount of substance present based on his results? Explain. 4 MARKS

Question 14 (2 MARKS)

A student decided to investigate the effect of temperature on the rate of the following reaction.

$2HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$

Part of the student's experimental report is provided below.

Method

1. Put 0.6 g of $CaCO_3$ chips into a conical flask.
2. Put a reagent bottle containing 2 M HCl into a water bath at 5 °C.
3. When the temperature of the HCl solution has stabilised at 5 °C, use a pipette to put 10.0 mL of the HCl solution into the conical flask containing the $CaCO_3$ chips.
4. Put a balloon over the conical flask and begin timing.
5. When the top of the balloon has inflated so that it is 10 cm over the conical flask, stop timing and record the time.
6. Repeat steps 1–5 using temperatures of 15 °C, 25 °C, 35 °C and 45 °C.

What does the student need to do to ensure that they comply with all applicable safety guidelines during the investigation?

Adapted from VCAA 2020 exam Short answer Q9a

Question 15 (6 MARKS)

One of the methods currently used to develop vaccines involves scientists intentionally infecting individuals with viruses, bacteria or parasites. Individuals can be given a vaccine against a particular disease and exposed to the pathogen responsible for the disease. In doing so, scientists are able to determine whether or not the vaccine is effective by measuring the extent to which the person shows symptoms of being ill. In comparison to traditional methods of vaccine development, this method is much quicker and requires only a few rounds of testing.

Alternatively, scientists can spend years developing vaccines that are rigorously tested in other contexts before being trialled on humans.

a. Identify the main concern discussed in the given passage. 1 MARK

b. Identify one reason why scientists would choose to conduct experiments on humans. 2 MARKS

c. Discuss the major disadvantages of both methods of vaccine development. 3 MARKS

Question 16 (5 MARKS)

Elephant toothpaste can be made using reactants such as hydrogen peroxide.



A section from the SDS for hydrogen peroxide is shown:

Section 2: Hazard(s) identification		
2.1. Classification of the substance or mixture		
GHS-US classification		
Oxidising liquids category 1	H271	May cause fire or explosion, strong oxidiser
Acute toxicity (oral) category 4	H302	Harmful if swallowed
Acute toxicity (inhalation) category 4	H332	Harmful if inhaled
Skin corrosion/irritation category 1A	H314	Causes severe skin burns and eye damage

a. Identify two pieces of personal protective equipment that would allow you to safely conduct this experiment. 2 MARKS

b. As part of the preparation for this experiment, a student asked the lab technician, who is not involved in the implementation of the method, to develop a risk assessment. Is the lab technician the appropriate person to develop the risk assessment? Explain. 3 MARKS

Question 17 (2 MARKS)

A student designed an experiment to investigate current efficiency during the electrolysis of a sodium chloride, NaCl, solution.

All experimental work was carried out under standard laboratory conditions (SLC). The experiment involved the use of a Hoffman electrolysis apparatus.

a. Identify a safety risk associated with the chemicals produced during the experiment. 1 MARK

b. What are the safety measures required to reduce the safety risk identified in part **a**? 1 MARK

Adapted from VCAA 2018 Short answer Q9bi, ii

Question 18 (4 MARKS)

Jo wanted to determine the concentration of different minerals in bottled mineral water. As part of the investigation, three different brands of mineral water were used.

a. Identify the independent variable. 1 MARK

b. List three variables that should be kept constant throughout the experiment. 3 MARKS

Question 19 🌶🌶🌶 (7 MARKS)

The following is an excerpt from a research article:

> **Background**
>
> Dietary sugar, especially in liquid form, increases risk of dental cavities, adiposity, and type 2 diabetes. The United Kingdom Soft Drinks Industry Levy (SDIL) was announced in March 2016 and implemented in April 2018 and charges manufacturers and importers at £0.24 per litre for drinks with over 8 g sugar per 100 mL (high levy category), £0.18 per litre for drinks with 5 to 8 g sugar per 100 mL (low levy category), and no charge for drinks with less than 5 g sugar per 100 mL (no levy category). Fruit juices and milk-based drinks are exempt. We measured the impact of the SDIL on price, product size, number of soft drinks on the marketplace, and the proportion of drinks over the lower levy threshold of 5 g sugar per 100 mL.
>
> *Source: https://journals.plos.org/plosmedicine/article?id=10.1371/journal.pmed.1003025*
>
> *Citation: Scarborough, P., Adhikari, V., Harrington, R. A., Elhussein, A., Briggs, A., Rayner, M., Adams, J., Cummins, S., Penney, T., & White, M. (2020). Impact of the announcement and implementation of the UK Soft Drinks Industry Levy on sugar content, price, product size and number of available soft drinks in the UK, 2015–19: A controlled interrupted time series analysis. PLoS medicine, 17(2), e1003025.*

a. Based on the information, write a hypothesis for what will happen to the proportion of drinks with over 5 g sugar per 100 mL as a result of the introduction of SDIL. 2 MARKS

b. What is the primary type of ethical concern in this experiment? 1 MARK

c. Describe a potential implication of the SDIL and how it would affect society. 4 MARKS

12C Interpreting data

STUDY DESIGN DOT POINTS

- ways of organising, analysing and evaluating primary data to identify patterns and relationships, including sources of error and uncertainty
- observations and investigations that are consistent with, or challenge, current scientific models or theories
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the key findings and implications of the selected scientific investigation

12A 12B **12C** 12D 12E

- 4.3.6.1 & 4.3.7.1 Identifying patterns in data
- 4.3.8.1 & 4.3.9.1 Drawing conclusions from data
- 4.3.10.1 Linking chemical concepts to conclusions

ESSENTIAL PRIOR KNOWLEDGE

12A A scientific method
12B Quantitative data
12B Qualitative data
See questions 98–100.


Image: metamorworks/Shutterstock.com

Why is data the key finding in an investigation?

Collecting data is a key part of scientific investigation. In this lesson, we will learn about the different ways in which we can interpret and represent data obtained from an experiment.

KEY TERMS AND DEFINITIONS

Anecdote the communication of an abstract idea about a person, place, or thing through the use of a story or narrative

Control group (controlled variables) sample that is subjected to the same conditions as all other samples without the independent variable

Opinion a view or judgement formed about something, not necessarily based on fact or knowledge

Identifying patterns in data 4.3.6.1 & 4.3.7.1

Experiments can show a relationship between the variables being studied (figure 1) and need to be identified as part of a scientific process.

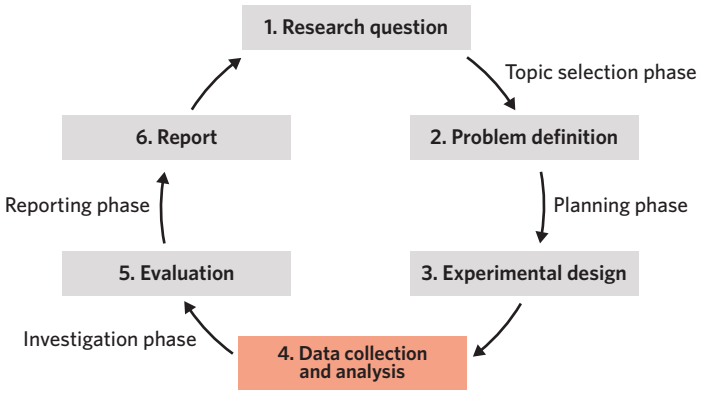


Figure 1 A scientific method

How can patterns in data be identified?

The main purpose of an experiment is to identify a possible relationship between the independent and dependent variable. Unless there are errors in the methodology of the experiment, we will generally be able to see a pattern emerge from the data collected.

The way we present data can make trends easier to identify. For example, it is easier to identify trends in quantitative data when it is represented as a line graph than it would be if the same data was presented as a pie chart. Table 1 shows the common forms of data representation and the type of data they are mostly used for.

Table 1 Characteristics of common data representation formats

Type of data representation	Example	Type of data being represented	Advantage
Line graph	Calibration curves	Quantitative	Useful for displaying trends over time and for predicting trends over time
Bar charts/graph	Water sampling in different areas	Both qualitative and quantitative	Easy to visualise and compare different categories of data
Pie chart/graph	Composition of fuel	Both qualitative and quantitative	Used to show proportions (e.g. percentages)
Table	Redox titration	Both qualitative and quantitative	Helps to organise and compare multiple sets of values

When constructing and analysing graphs, it is important to know the variable that is being represented on each axis. In figure 2, the y-axis represents the dependent variable, whereas the x-axis represents the independent variable.

When interpreting graphs, we need to think about how the independent variable affects the dependent variable. For example, consider the graph shown in figure 3. In the graph, we can see that the dosage of medicine given to a dog (vertical axis) increases as the weight of the dog (horizontal axis) increases.

Regardless of whether we are interpreting our own data collected from our experiment, or experimental data in a journal article, we are using the same strategy to identify trends. Being able to do so will help us determine the accuracy of the claims made by experimenters about their own research.

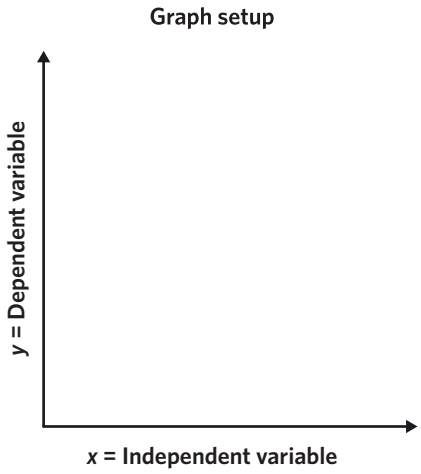


Figure 2 Representation of data in graphs

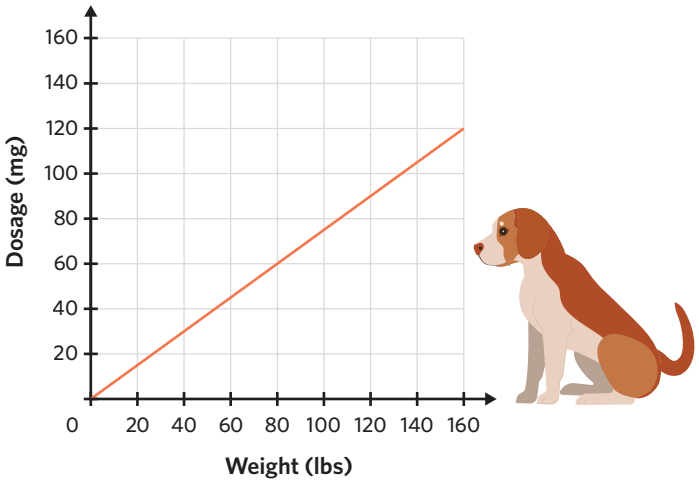
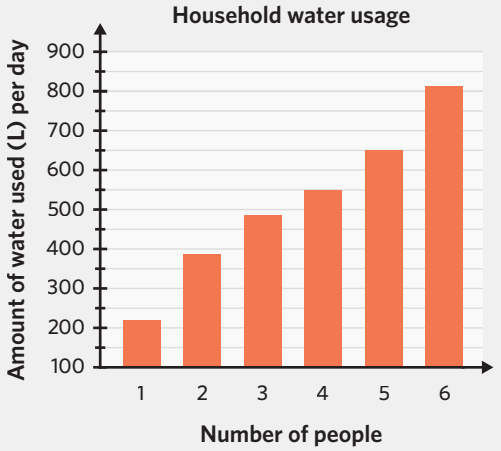


Figure 3 Graph showing information about the dosage of medicine for dogs (2.2 lbs = 1 kg)

WORKED EXAMPLE 1

Water companies use data to estimate the water usage of different sized households. The graph provided shows the amount of water used based on the number of people in the house per day.

Predict the amount of water used in a household per day containing seven people.



What information is presented in the question?

A bar graph representing water usage.

What is the question asking us to do?

Predict the amount of water used in a house with seven people.

What strategies do we need in order to answer the question?

1. Identify the general trend in the data presented in the graph.
2. Find the average change in the amount of water used as the number of people increases.
3. Determine a possible range for the water used per day for seven people.

Answer

Overall, it can be seen that the more people there are in the household, the more water is used per day.

Upon closer analysis of the increase in water usage per person added, it can be seen that on average, there is approximately a 135 L increase with each additional person.

Therefore, it is predicted that in a house of seven people, the water usage could range from approximately 920–960 L.

BPA SCIENTIFIC INQUIRY

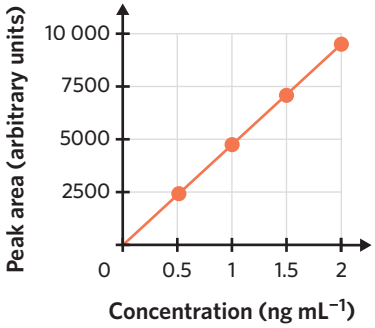


Figure 4 Calibration curve of known standards of BPA

Figure 4 shows the calibration curve developed from the use of BPA standards. As the concentration of BPA increases, the area under the curve also increases. We can use this graph to identify the concentration of BPA in the different samples in our experiment by cross referencing these values with the calibration curve.

Based on figure 5, it can be concluded that when three BPA bottles are left at a higher temperature, there is an increase in the concentration of BPA in the water. Three non-BPA bottles (E–F) were also tested as a **control group (controlled variables)** and did contain trace amounts of BPA (see lesson 12E) which are too small to be displayed on figure 5.

BPA SCIENTIFIC INQUIRY

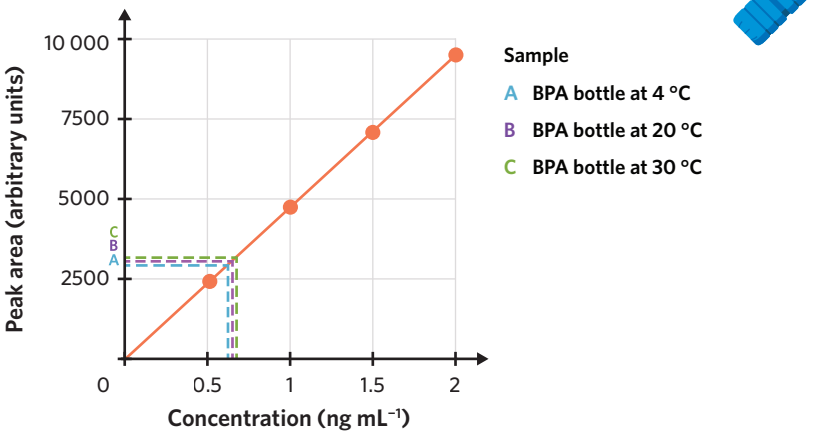


Figure 5 Determination of the concentration of BPA in samples A–C

What graphical representations can be used in VCE chemistry?

Graphical representations can be used to more clearly show whether any trends, patterns, or relationships exist in data.

The type of graphical representation used will depend on the type of scientific investigation methodology and the type of variables investigated:

- Pie graphs and bar charts can be used to display data in which one of the variables is categorical.
- Scattergrams can be used to show an association between two variables.
- Line graphs can be used to display data in which both the independent and dependent variables are continuous.
- Lines, or curves, of best fit can be used to illustrate the underlying relationship between variables.
- Sketch graphs (not necessarily on a grid; include no plotted points; include labelled axes that are not necessarily scaled) can be used to show the general shape of the relationship between two variables.

When drawing graphs:

- Pie charts should be drawn with the sectors in rank order, largest first, beginning at 'noon' and proceeding clockwise.
- Pie charts should preferably contain no more than six sectors.
- Bar charts should be drawn when one of the variables is not numerical.
- Bar charts should be made up of narrow blocks of equal width that do not touch.
- Not all experiments will show a correlation between variables; it is possible that another variable causes them both or the correlation may be attributable to chance alone.
- The existence of a correlation does not necessarily establish that there is a causal relationship between two variables.
- Unless instructed otherwise, or unless other conventions or usefulness apply, the independent variable should be plotted on the x-axis (horizontal axis) while the dependent variable should be plotted on the y-axis (vertical axis).
- All graphs should have a title that includes reference to the independent and dependent variables.
- All graph axes should be labelled with the physical quantity and the appropriate unit; for example, time (seconds).
- The scales for the axes should be appropriately spaced to allow more than half of the graph grid to be used in both directions.
- Points on a graph should be clearly marked: students may use crosses (×), dots (●) or circled dots (⊙).
- A line of best fit (trend line) should be a single, thin, smooth straight-line or curve and does not need to coincide exactly with any of the points; a roughly even distribution of points either side of the line over its entire length should be drawn.
- Points that are clearly anomalous should be further investigated in order to ethically deal with data; if possible, the experiment to generate the data point should be repeated.
- Graphs should not be forced through (0, 0) even if this is a data point.

Adapted from VCAA 2022 Chemistry Graphical Representations

PROGRESS QUESTIONS

Question 1

Experimental data can be shown as a

A. line graph.
B. bar graph.
C. pie chart.
D. all of the above.

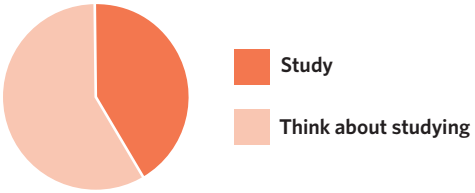
Question 2

The type of data collected helps to determine the

A. way in which data is presented.
B. dependent variable in the experiment.
C. independent variable in the experiment.
D. controlled variables.

Question 3

The figure shown would be best used to represent



A. the proportion of students who think about studying.
B. the number of students who think about studying.
C. the number of students who study.
D. the number of students.

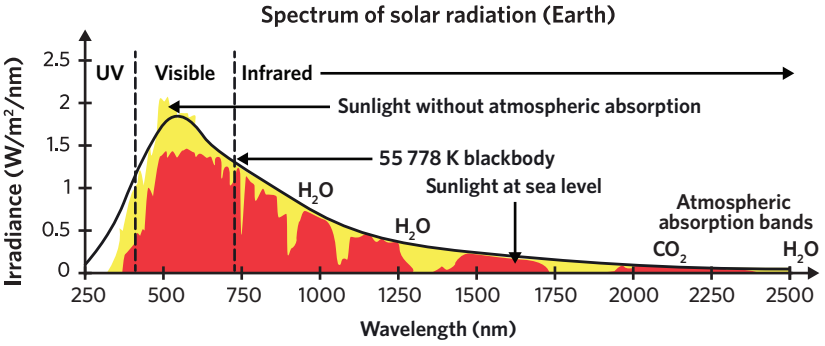
Question 4

Generally speaking, experimental data shows

A. trends between the controlled and independent variables.
B. trends between the controlled and dependent variables.
C. trends between the controlled variables.
D. trends between the independent and dependent variable.

Question 5

In the graph shown, wavelength represents the



A. controlled variables.
B. dependent variable.
C. independent variable.
D. trend line.

Continues →

Question 6

In the graph provided in question 5, the _____ is affected by the _____

A. wavelength, irradiance.

B. irradiance, wavelength.

C. wavelength, controlled variables.

D. irradiance, controlled variables.

Drawing conclusions from data 4.3.8.1 & 4.3.9.1

The trends represented by experimental data can help us develop a better understanding of the scientific theory related to the research. Conclusions drawn from data must be limited by, and not go beyond, the data available.

How do we make conclusions about data?

The data collected through scientific research can help address the hypothesis, and the nature of this data is distinct from non-scientific **opinion** and **anecdote**.

Examples of these non-scientific ideas include opinions, which are personal views that do not necessarily stem from fact or the scientific method, and anecdotes, which are personal experiences that may illustrate a scientific point, but again are not necessarily aligned with a scientific method (table 2). The results of an experiment do not necessarily have to support the hypothesis; in fact, the greatest learnings come from experiments where the data collected challenges the hypothesis.

Table 2 Scientific ideas vs opinions vs anecdotes

	Scientific ideas	Opinions	Anecdotes
Definition	Ideas developed according to the scientific method	Personal views: not necessarily aligned with scientific method	Personal experience: not necessarily aligned with scientific method
Example	'The boiling point of water is 100 °C.'	'I think that all Geminis are untrustworthy.'	'A Gemini once stole my lunch.'

Firstly, to know that the trend in the experimental data collected was due to the independent variable, we need to make sure that a control group is present as a point of comparison to show that any change in the experiment was due to the impact of the independent variable. A control in an experiment is set up in a way that doesn't allow the independent variable to impact the results (i.e. the independent variable is not applied or changed in the control sample). This is important as it allows us to attribute the changes in the experiment to the independent variable, and the effect of other variables.

BPA SCIENTIFIC INQUIRY



Back to our experiment. Of the six samples, samples A–C involve BPA-containing bottles, whereas D–F do not. The purpose of D–F is to act as a control to show that the changes in BPA concentration were due to the BPA present in the bottles that were subjected to different conditions, instead of just the change in temperature. To ensure the quality of our experiment, all other variables, such as volume of water and duration of the experiment were controlled (and therefore were the controlled variables).

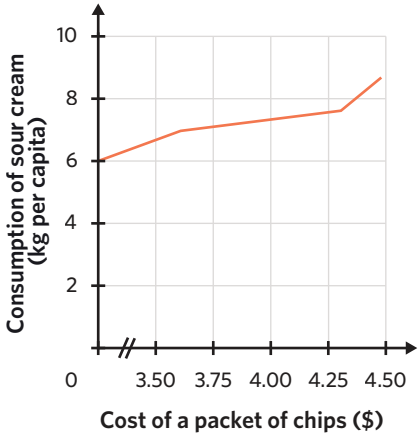


Figure 6 Line graph representing the relationship between sour cream consumption and cost of chip packets

One point to remember is that the trends seen in the data collected in an experiment do not necessarily illustrate a causal relationship; that is, it does not mean that the changes seen in the dependent variable are solely due to the independent variable. There may be a correlation, which means that the changes observed in the dependent variable are associated with the independent variable, but it is possible that other variables could also be responsible for this change. As such, we cannot say that the result was caused by the independent variable; we cannot establish causation. For example, based on the data presented in figure 6, it can be seen that as the cost of a packet of chips increases, the amount of sour cream consumed also increases. However, this does not necessarily mean the cost of chips is the reason why people eat more sour cream.

Furthermore, there may be factors that affect the validity and reliability of our conclusions – a concept that we will explore in lesson 12D. For our water bottle experiment, we need to analyse the data to understand the implications of our observations. This will be the bulk of the discussion section of our experimental report.

BPA SCIENTIFIC INQUIRY



Discussion

Compared to the control group samples D–F in which water was placed in a BPA-free bottle, the presence of BPA in the water bottles (A–C) resulted in a greater concentration of BPA in the water samples. For samples A–C, it can be seen (figure 5) that an increase in temperature is correlated with an increase in the concentration of BPA measured. The samples placed in the 30 °C and 20 °C environments and in the fridge (4 °C) measured BPA concentrations in ng mL^{-1} of 0.63, 0.61 and 0.58 respectively. BPA can be released into the contents of water bottles when the plastic begins to degrade. As shown in previous studies, an increase in temperature results in an increase in the degradation of plastic (Biedermann-Brem & Grob., 2008). In particular, an increase in temperature results in the increase in the rate at which the plastics are degraded. In the context of BPA-containing plastic water bottles, this could lead to an increase in the rate at which BPA is released into the water. This trend is shown in the results of this experiment. As can be seen in the experimental results, there was a greater concentration of BPA found in the sample subjected to the highest temperature (sample C) given that all samples were tested over the same period of time. It is possible then that at higher temperatures, there could be a greater release of BPA from plastic, resulting in a higher concentration of BPA recorded.

PROGRESS QUESTIONS

Question 7

'I've noticed that people tend to drive more slowly when it rains.'

This statement is an example of a(n)

A. anecdote.

B. scientific idea.

C. opinion.

D. None of the above

Question 8

For an experiment measuring the effect of the amount of water used on the growth of a sunflower seed, a suitable control group would be

A. a sunflower seed receiving no water.

B. a sunflower seed receiving water on one day and then no water another day.

C. a sunflower seed receiving half the amount of water compared to all of the other sunflower seeds.

D. a sunflower seed receiving twice the amount of water compared to all of the other sunflower seeds.

Continues →

Question 9

The following statement was made about an experiment. 'As the temperature increases, it can be seen that students complete more homework.'

In this experiment, it is most likely that

A. the change in temperature causes students to do less homework.

B. the change in temperature is not related to students completing homework.

C. the change in temperature causes students to do more homework.

D. the change in temperature is related to students completing homework.

Linking chemical concepts to conclusions 4.3.10.1

The conclusions developed from research need to be explained by scientific theory.

How do we link the chemistry into the conclusions?

When evaluating research, the conclusions drawn need to be supported both by the experimental data collected during the experiment as well as existing theory. Regardless of whether or not the hypothesis is supported, it is important that we recognise the scientific theory that could explain the observations made.

The research you will conduct this year will be mainly based around the concepts that you will be learning about. These are briefly outlined in table 3.

Table 3 Key research concepts in VCE chemistry Units 3 & 4

Concept	Brief description
Fuels	Amount of energy produced
Redox reactions in cells	Transfer of electrons between oxidation and reduction reactions
Equilibrium	Extent of chemical reactions
Concentration	Amount of a substance in a given volume of water

In our water bottle experiment, the main ideas related to the experiment involve

- concentration
- bonding
- temperature and the rate of reactions.

As a result, discussions about and explanations of the data need to be based on our current understanding of these key ideas. This thought process also applies when we evaluate other research.

PROGRESS QUESTIONS

Question 10

It is sometimes difficult to prove causation because

A. results are always affected by a different variable.

B. results are always affected by the same variable.

C. results can be affected by multiple factors.

D. results cannot be affected by multiple factors.

Continues →

Question 11

Conclusions in research will _____ prove a hypothesis correct.

A. sometimes

B. always

C. never

D. All of the above

Theory summary

- Results generally show a relationship between the independent and dependent variables.
- A control group is important to show that the changes were due to the variable being tested.
- Anecdote and opinion are not considered to be scientific.
- The way in which we represent data depends on the type of data collected.
- Conclusions generated from data need to be supported by scientific theory.

12C Questions

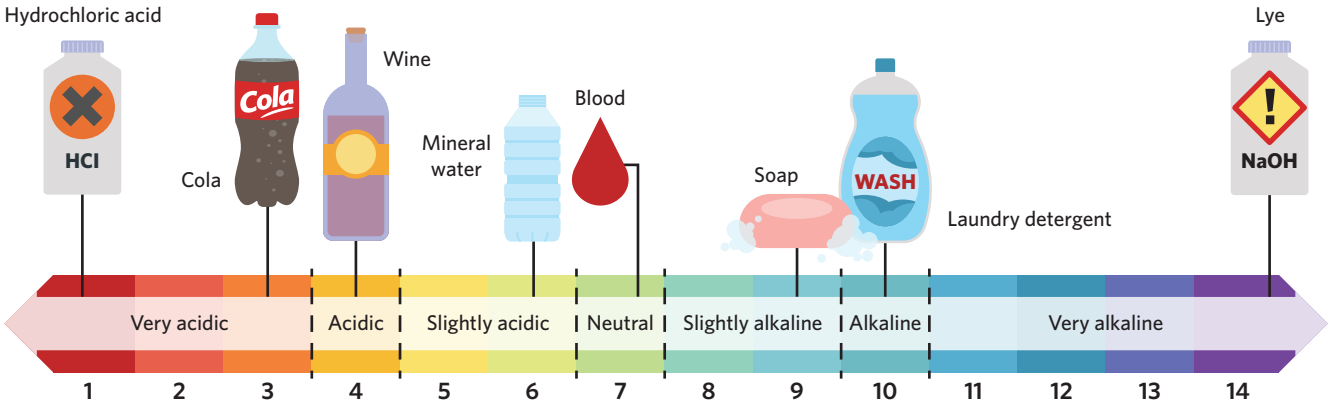
Mild Medium Spicy

Deconstructed

Use the following information to answer questions 12–14.

Scientists use pH to measure how acidic or basic substances are. For example, laundry detergents are considered basic, whereas wine is considered acidic.

pH Scale: What is Acidic, What is Alkaline?



Question 12 (1 MARK)

Substances that are neutral have a pH of approximately

A. 5 **B.** 6 **C.** 7 **D.** 8

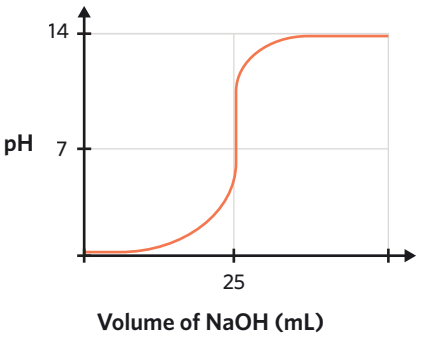
Question 13 (1 MARK)

Generally speaking, when cola is added to water, the solution would become

A. more acidic. **B.** more basic. **C.** less acidic. **D.** neutral.

Question 14 (2 MARKS)

The graph provided shows the pH levels in a solution to which lye (NaOH) was added over time.



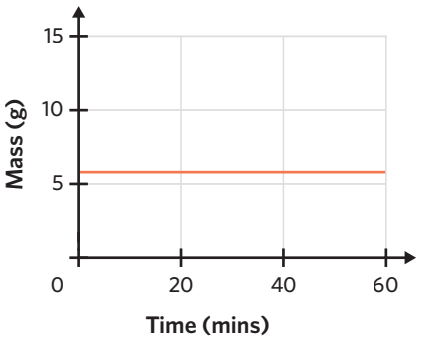
Would the original solution (before NaOH was added) be considered as acidic or basic? Explain.

Exam-style

Question 15 (3 MARKS)

Our current understanding of science is built from the knowledge developed through a large body of research.

Consider the following graph, which represents data collected from an experiment, where a sealed beaker containing a chemical reaction was left on a mass balance and weighed over time.



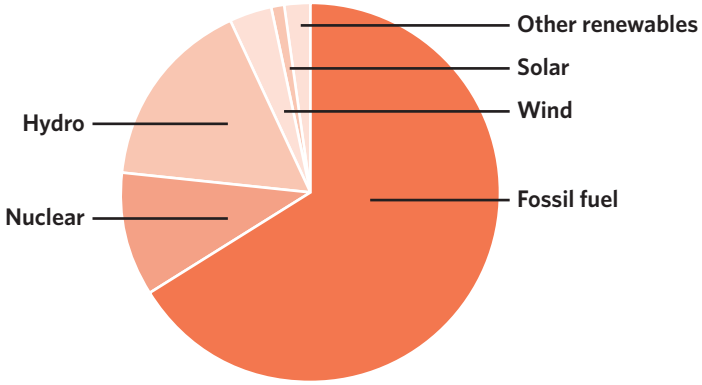
a. Identify the trend shown in the graph. 1 MARK

b. Use one of the following chemical concept(s) to justify the conclusion(s) drawn from the graph provided. 2 MARKS

- The law of conservation of mass states that no mass is ever lost or gained overall.
- Energy is never 'lost'; it is merely transformed.
- There are approximately 6.02×10^{23} atoms/molecules/ions in a mol.

Question 16 (4 MARKS)

The world requires different types of energy in order to sustain all of the work that occurs.
The graph provided shows the world's electricity sources in 2020.

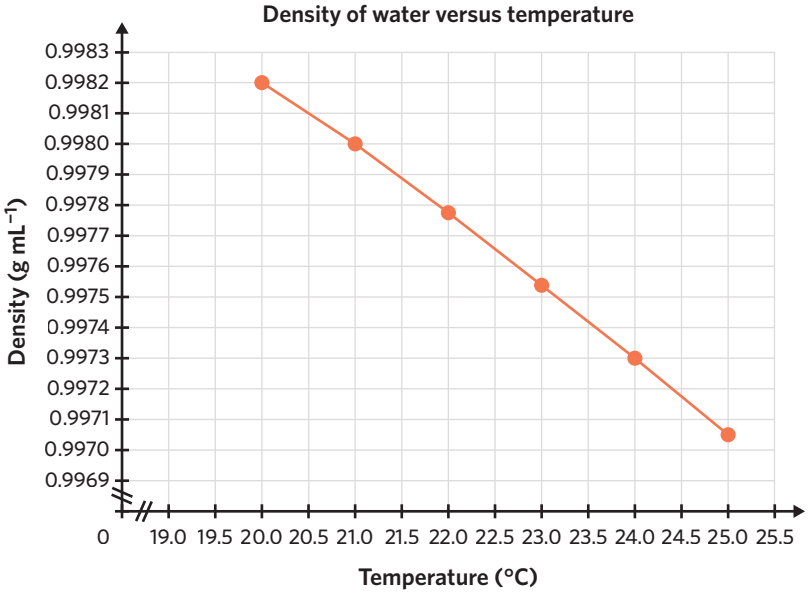


a. Identify the overall breakdown of energy sources shown in the graph. 1 MARK

b. Fossil fuels are formed over millions of years and are generally extracted through deep drilling into the earth. The use of fossil fuels produces substances such as carbon dioxide, sulfur dioxide and nitrogen oxides. Given that the Earth's population continues to grow, what would be expected to occur over the next 10 years with respect to the usage and impact of fossil fuels? 3 MARKS

Question 17 (2 MARKS)

The following graph shows the variation in the density of water with temperature.



a. Why do both axes have a break in the sequence of numbers? 1 MARK

b. What conclusion can be drawn from the data shown in the graph? 1 MARK

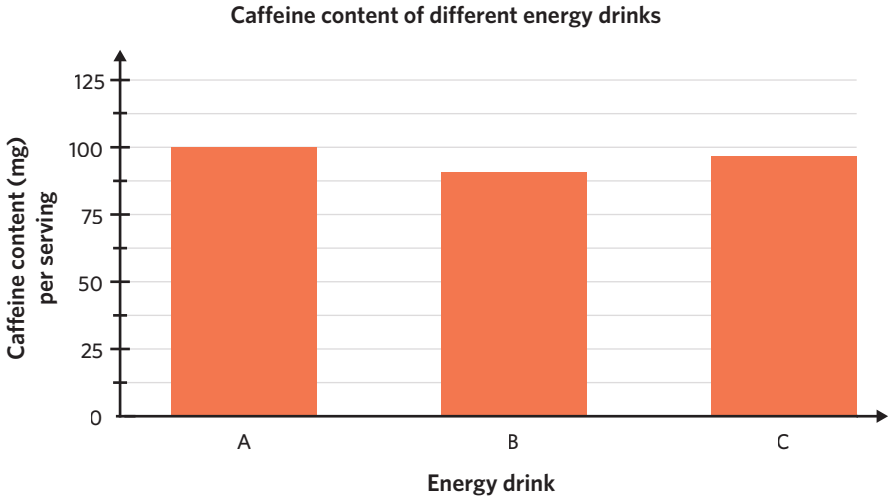
Adapted from VCAA (NHT) 2019 exam Short answer Q6

Question 18 (5 MARKS)

Energy drinks that contain a large amount of caffeine are becoming increasingly popular among teenage students. On average, each serving contains approximately 100 mg of caffeine, which is over double the amount of caffeine contained in a soft drink. A student wished to study the caffeine content in various brands of energy drinks (A, B and C).

a. What type of data would be collected in the experiment? 1 MARK

b. The student presented the data in the graph shown.



What is the general information presented in this graph? 1 MARK

c. At high levels, caffeine is known to cause symptoms such as

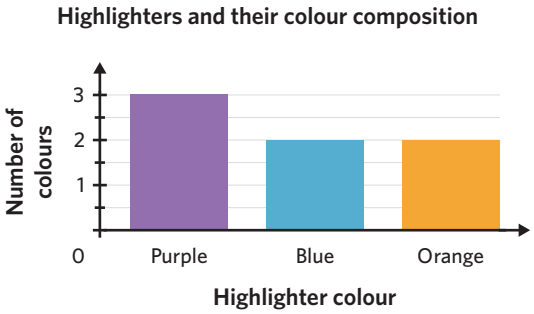
- headaches,
- sleeping problems and
- increase in heart rate.

To further investigate the impact of caffeine on adolescents, the student proposed an experiment involving their friends. Identify a major ethical concern of this experiment. 2 MARKS

d. Given that the student wanted to investigate the impact of caffeine-containing energy drinks on sleep, identify a suitable control for the experiment. 1 MARK

Question 19 (3 MARKS)

A student wanted to conduct an experiment to determine the composition of different coloured highlighter pens. The graph provided shows the results of the experiment.



a. Identify the dependent variable. 1 MARK

b. List two variables that need to be kept constant throughout the experiment. 2 MARKS

12D Experimental factors affecting data

STUDY DESIGN DOT POINTS

- the quality of evidence, including validity and authority of data and sources of possible errors or bias
- authentication of generated primary data through the use of a logbook
- conventions of science communication: scientific terminology and representations, symbols, formulas, standard abbreviations and units of measurement
- assumptions and limitations of investigation methodology and/or data generation and/or analysis methods



Image: Kiselev Andrey Valerevich/Shutterstock.com

How do we judge the quality of the data collected?

In this lesson, we will learn about the factors that affect the quality of the data collected during an experiment and how this can impact the research findings.

12A 12B 12C **12D** 12E

- 4.3.9.2 & 4.3.11.1 Sources of error and bias
- 4.3.12.1 Precision and accuracy
- 4.3.12.2 Validity and the three R's
- 4.3.13.1 Significant figures in reports
- 4.3.14.1 Limitations of data

ESSENTIAL PRIOR KNOWLEDGE

12C Drawing conclusions

See question 101.

KEY TERMS AND DEFINITIONS

Accuracy how close measured values are to their true value

Bias difference between the average of a large set of measurements and the true value

Error difference between the measured value and the true value

Method specific steps and techniques required to collect, visualise, and analyse experimental data in a scientific investigation

Methodology different ways in which the planning and conducting of scientific investigations can be carried out

Mistake sometimes called personal errors, mistakes should not be included in reporting and analysis

Outlier data point or observation that differs significantly from other data points or observations

Precision how close measured values are to each other

Random error usually a 'one-off' error in measurement that differs in amount between trials

Repeatability closeness of the agreement between the results of successive measurements of the same quantity, carried out under the same conditions

Reproducibility closeness of the agreement between the results of measurements of the same quantity, carried out under changed conditions

Resolution (measurement) the smallest change in quantity that is measurable (by a particular instrument)

Significant figures number of digits required to express a number to a certain level of accuracy

Systematic error error in measurement by the same amount in the same direction every time, which also includes errors that are inherent in the experiment

Uncertainty level of doubt regarding the data obtained (for VCE purposes, we are only looking at this from a qualitative perspective)

Validity whether the experiment and its components including the results address the aim and hypothesis of the research

Sources of error and bias 4.3.9.2 & 4.3.11.1

Errors can affect the overall results collected during data analysis and are an important part of the scientific process (figure 1).

Why do we need to know about errors?

The **uncertainty** of the result of a measurement reflects the lack of exact knowledge of the value of the quantity being measured. VCE chemistry requires only a qualitative treatment of uncertainty. When conducting experiments, we always try to make sure that the conditions are well controlled. However, there is still a chance that errors can occur. These errors ultimately affect our results, creating a level of uncertainty in the data collected during the experiment. The main sources of error stem from two main types of errors: **systematic** and **random errors**.

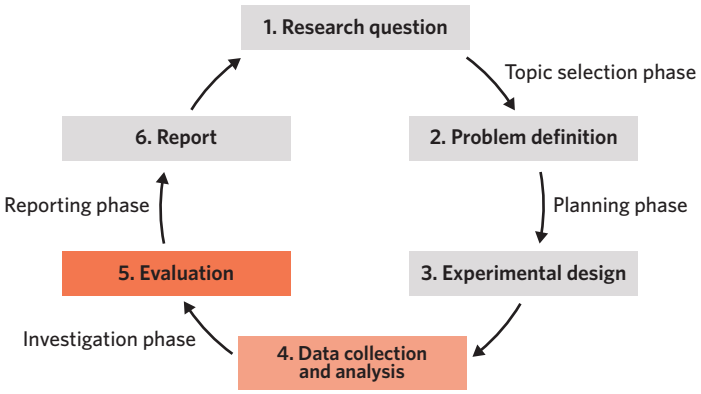


Figure 1 A scientific process

Systematic errors

Systematic errors cause measurements to differ from their true value in a systematic manner so that when a particular value is measured repeatedly, the error is always the same. These systematic errors can arise from limitations in the instruments used, incorrect calibration of instruments, or the use of inappropriate measuring **methods** (including the parallax error). A common example involves the reading of measuring cylinders, as shown in figure 2.

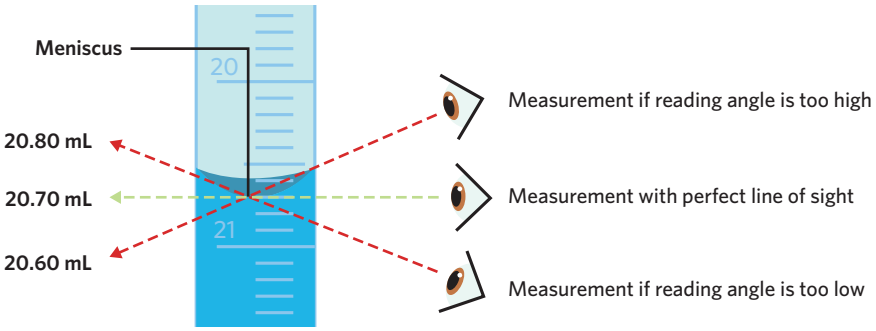


Figure 2 Errors that can arise during the use of measuring cylinders

To reduce the effect of systematic errors, we should calibrate all apparatus before conducting the experiment and analyse the method to identify steps that could introduce errors. Understanding correct measuring techniques is also beneficial.

BPA SCIENTIFIC INQUIRY



For the BPA experiment, a systematic error could occur in the volume of water in the water bottles used. Since the labelling was trusted on the unopened bottles, it was assumed that they contained the correct volume of water. A way to rectify this error would be to measure the exact volume of water using scientific apparatus. Since this could also introduce a parallax error, care must be taken to ensure the use of the appropriate technique.

Random errors

Random errors affect the **precision** of a measurement and may be present in all measurements. These errors are unpredictable variations in the measurement process and result in a spread of readings. For example, a random error can occur when the volume of a liquid needs to be estimated as a consequence of using a measuring cylinder that is missing lines or numbers. We can minimise this type of error by repeating experiments multiple times to calculate the average of the results. Systematic and random errors affect an experiment in different ways as shown in figure 3.

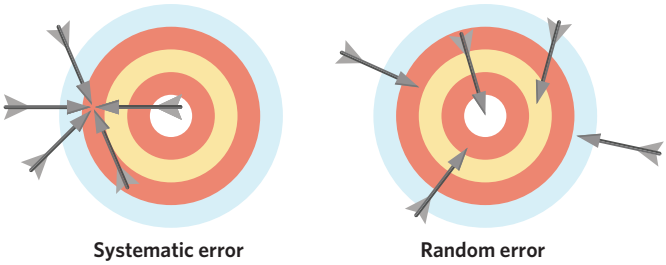


Figure 3 Effect of systematic and random errors on an experiment

From the perspective of a graph, systematic errors will cause the whole graph to be shifted by the same degree. The trend shown as a result of both errors is generally still the same. However, the values will be different to the true value. With respect to random errors, we would have to draw a line of best fit. The effect of both systematic errors and random errors are depicted in figure 4.

We can use the measured values to determine the difference between the average of repeated experiments and the data (inclusive of systematic errors), which is referred to as **bias**. The best way to minimise bias would be to minimise both types of errors in an experiment.

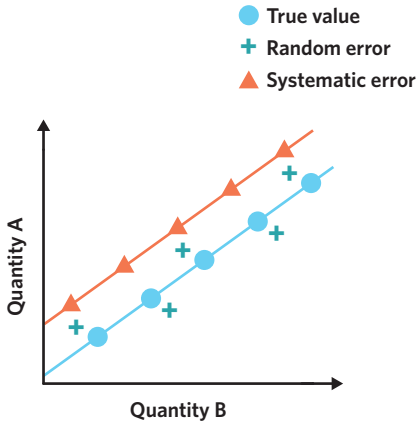


Figure 4 Graphical representation of the effect of systematic and random errors

MISCONCEPTION

'Personal errors are a type of error.'

Despite their name, personal errors/ mistakes are not a type of error and must not be included in scientific reporting.

BPA SCIENTIFIC INQUIRY



In regards to the water bottle BPA experiment, a mistake that could occur may involve the extraction of a sample of pure BPA using a pipette that measures mL instead of µL for one of the samples.

Mistakes

Mistakes are sometimes called personal errors. Mistakes should not be included in reporting and analysis as part of the ethical consideration of data handling. Rather, the experiment should be repeated correctly. Fortunately, mistakes can be minimised by repeating the experiment properly.

Detecting errors in research

Errors can have a significant impact on the quality of research. Therefore, it is important that we are able to identify errors in research that we read. This can range from theoretical misinterpretations, to analytical and measurement errors, as mentioned previously. Some questions that could be useful in identifying analytical and measurement errors are:

- Are there **outliers** in the data? If so, why?
- Were the measuring instruments calibrated?
- Is the **methodology** prone to misinterpretation? (i.e. are any of the steps in the methodology ambiguous?)
- What is/are the expected value(s)? How far is the data collected in the experiment from the expected value(s)?

Being able to detect these types of errors will depend on:

- A deep understanding of the related theoretical concepts
- Understanding the common methodology used for the type of experiment being conducted

The best places to find these errors will be in the methods and results section of the research paper.

PROGRESS QUESTIONS

Question 1

Which of the following is **not** a systematic error?

A. Spilling an alkaline solution on the bench top

B. Using a 100 mL measuring cylinder to measure all solutions of less than 10 mL

C. Using an analytical balance that is not calibrated

D. Using a value of 25 mL from a pipette that can measure 25.0 mL of acid

Question 2

Which of the following is **not** a random error?

A. Stirring error

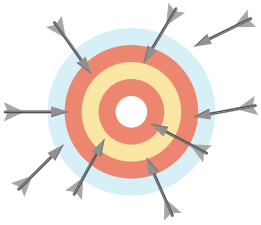
B. Using two different indicators in a titration

C. A parallax error

D. Forgetting to add a reagent

Question 3

The diagram shown represents



A. systematic errors.

B. random errors.

C. only one error.

D. no errors.

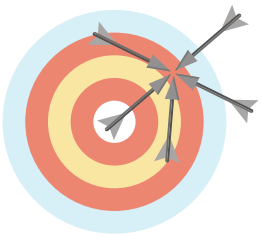
Precision and accuracy 4.3.12.1

Precision and **accuracy** affect experimental results in different ways.

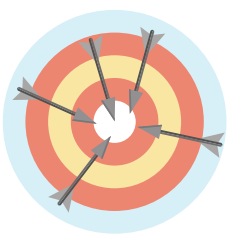
How do precision and accuracy differ?

Precision is the measure of the **repeatability** or **reproducibility** of scientific measurements and refers to how close two or more measurements are to each other. A set of precise measurements will have values very close to the mean value of the measurements. Precision gives no indication of how close the measurements are to the true value and is therefore a separate consideration to accuracy. Precision is primarily impacted by random errors. For experiments that require estimation of results, the measurements taken may not be very precise. For example, this can occur during experiments where we are asked to identify changes in colour that are similar.

Accuracy refers to how close a measured value is to its true value. It is a qualitative term, meaning that it can describe a measurement value or result as being 'less accurate' or 'more accurate' when compared with a true value. As shown in figure 5, measurements that are precise are not necessarily accurate; in fact, measurements can differ from the true value but still be considered precise.

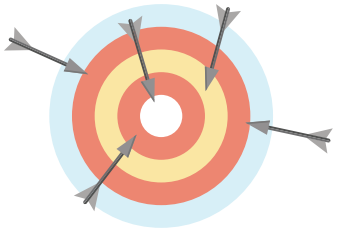


High precision and low accuracy

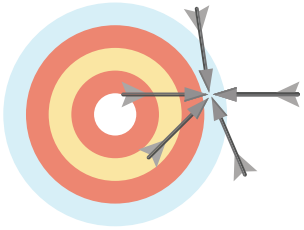


High precision and high accuracy

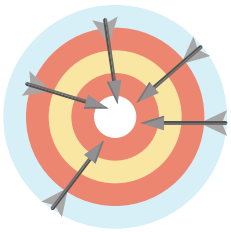
Figure 5 Comparison between precision and accuracy



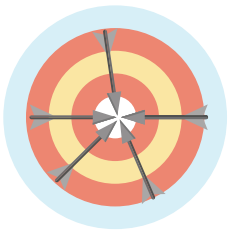
Low accuracy
Low precision



Low accuracy
High precision



High accuracy
Low precision



High accuracy
High precision

Figure 6 Illustration of the categorisation of data

It is also possible to collect data that is highly accurate yet not precise if the values are not close to each other. We can therefore categorise data based on both accuracy and precision. This concept is illustrated in figure 6.

The accuracy of data collected during an experiment is affected by the presence of systematic errors in the experimental design, some of which may include:

- purity of the substances used
- use of poorly cleaned apparatus
- uncalibrated measuring instruments
- unclear experimental method.

To increase the accuracy of data collected, we need to try to remove any systematic errors that may be present in the experiment. To test the accuracy of our data, we can determine the measurement error of the results by finding the difference between the measured values and the true value.

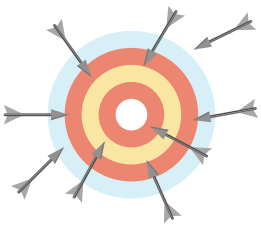
Validity refers to an experimental investigation that it sets out and/or claims to investigate. Both experimental design and the implementation should be considered when evaluating validity. An experiment and its associated data may not be valid, for example, if the investigation is flawed and controlled variables have been allowed to change. Data may not be valid, for example, if there is observer bias.

The collection of data that is both accurate and precise is important as it can affect the conclusions made from an experiment. It also affects the validity of an experiment, which refers to the ability of the results obtained through the particular experimental design to address the aim and hypothesis of a research study. To make sure that results are valid, we need to make sure that:

- The appropriate measuring instruments are used to collect accurate results.
- Controlled variables are kept constant.
- The experimental methodology is able to test the hypothesis.
- Data is collected under controlled and appropriate conditions.

PROGRESS QUESTIONS

Use the following diagram to answer questions 4–5.



Question 4

The diagram shows data that is

A. not precise.
B. very precise.
C. the true value.
D. close to the true value.

Question 5

For data shown to be accurate, the data points need to be

A. random anywhere on the target.
B. anywhere on the red and yellow circles.
C. as close as possible to the centre of the target.
D. clustered together anywhere on the target.

Validity and the three R's 4.3.12.2

Errors can affect the ability of an experiment to answer the research question.

How can an investigation be considered valid?

Unfortunately, not all experiments are considered valid. To ensure that experiments are able to test the aim and hypothesis, we need to make sure:

- We know what the independent variable is, and whether it relates to the research question.
- We know the dependent variable, and whether it is what we need to measure to answer the research question.
- We control all other variables.

There are three main ideas that are affected by the presence of errors, and hence determining the validity of an investigation.

Reproducibility is the closeness of the agreement between the results of measurements of the same quantity being measured, carried out under changed conditions of measurement. These changed conditions, involving replicate measurements on the same or similar objects, include a different observer, different method of measurement, different measuring instrument, different location, different conditions of use and different time. The purposes of reproducing experiments include checking of claimed precision and uncovering of any systematic errors that may affect accuracy from one or other experiments/groups. Experiments that use subjective human judgement or involve small sample sizes or insufficient measurements may also yield results that are not reproducible. Reproducibility links closely to the accuracy of an experiment. Reproducibility can also be used to evaluate the quality of data in terms of the precision of measurement results.

Repeatability is the closeness of the agreement between the results of successive measurements of the same quantity being measured, carried out under the same conditions of measurement. These conditions include the same observer, the same measurement procedure, the same measuring instrument used under the same conditions, the same location, and replicate measurements on the same or similar objects over a short period of time. Experiments that use subjective human judgement or that involve small sample sizes may yield results that may not be repeatable. Repeatability can be used to evaluate the quality of data in terms of the precision of measurement results. Ideally, measurements should be repeated where possible to produce a measurement result.

Resolution is the smallest change in the quantity being measured that causes a perceptible change in the value indicated on the measuring instrument. This has implications for determining the number of decimal places to which a quantity may be quoted. For example, if the resolution of a burette is 0.05 mL, then the user must estimate the volume between the two marked intervals on the burette so that the value reported will be to two decimal places. In this case, measurement readings of 10.50 mL or 10.55 mL are possible, but a measurement reading of 10.53 mL cannot be claimed. The meniscus of the liquid will either be on the burette line marking, in which case the reading would be 10.50, or it will lie between 10.50 and 10.60, in which case it is measured as 10.55 mL.

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Making sure that data is valid ensures that the evidence collected is strong. Having strong evidence means that the findings from the research study is more robust and believable. In contrast, weak evidence that is laden with errors is less likely to be accepted by the scientific community.

USEFUL TIP

Reliability is a term that will no longer be used in the current study design.

PROGRESS QUESTIONS

Question 6

Experiments with reproducible results

A. can be replicated by other experimenters under different conditions to yield similar results.

B. can be replicated by other experimenters under the same conditions to yield similar results.

C. can be replicated by the same experimenter under different conditions to yield similar results.

D. can be replicated by the same experimenter under the same conditions to yield similar results.

Question 7

Experiments with repeatable results

A. can be replicated by other experimenters under different conditions to yield similar results.

B. can be replicated by other experimenters under the same conditions to yield similar results.

C. can be replicated by the same experimenter under different conditions to yield similar results.

D. can be replicated by the same experimenter under the same conditions to yield similar results.

Significant figures in reports 4.3.13.1

Data is collected and expressed to various **significant figures**.

How do we determine the correct number of significant figures?

USEFUL TIP

Significant figures and decimal places are not the same thing.

Significant figures represent the precision of a measurement device. A measuring apparatus that expresses values to three significant figures is less precise than an electronic balance that expresses values to four significant figures.

Significant figures should be considered in all calculations. The following guidelines apply to VCE chemistry:

- All digits in numbers expressed in standard form are significant: for example, 5.320×10^{-6} has four significant figures.
- All non-zero numbers are significant. For example, 53.2 has three significant figures.
- Zeros between two non-zero numbers are significant. For example, 5.3203 has five significant figures.
- Leading zeros are not significant. For example, 0.0053 has two significant figures.
- Trailing zeros to the right of a decimal point are significant. For example, 53.00 has four significant figures.
- Whole numbers written without a decimal point will have the same number of significant figures as the number of digits, with the assumption that the decimal point occurs at the end of the number. For example, 500 has three significant figures. Therefore, a stated volume of '500 mL' will be considered as having three significant figures.

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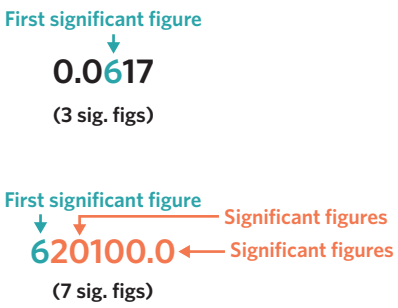


Figure 7 Consideration of significant figures

The appropriate use of significant figures is demonstrated in figure 7.

WORKED EXAMPLE 1

How many significant figures are found in the number 0.1104?

What information is presented in the question?

The number 0.1104.

What is the question asking us to do?

Determine the number of significant figures in 0.1104.

What strategies do we need in order to answer the question?

1. Leading zeros are not significant.
2. Zeroes between two non-zero numbers are significant.

Answer

According to the rules provided in the VCE Study Design, we start counting significant figures from the first non-zero number, which is the 1 immediately after the decimal place.

Since zeros that come after the first significant figure that are followed by a non-zero number are considered significant, the 0 after the 1 is considered significant.

Therefore, the number 0.1104 contains four significant figures.

When required to perform calculations, we need to express our answers to an appropriate number of significant figures. This depends on both the number of significant figures presented in the question, as well as the type of calculations that need to be performed:

- For addition/subtraction, answers are expressed with as many digits to the right of the decimal place according to the number with the least number of decimal places.
- For multiplication/division, answers are expressed with as many significant figures as the number with the least number of significant figures.

This is summarised in figure 8.

$4.88 + 3.9 = 8.8$

Answer is expressed to 1 decimal place (based on 3.9)

$2.7 \times 1.11 = 3.0$

Answer is expressed to 2 significant figures (based on 2.7)

Figure 8 The strategies involved in expressing quantitative values from a calculation

WORKED EXAMPLE 2

As part of her calculations, Judee performed the following step:

$= \frac{2.11}{1.3}$

How many significant figures would her answer be expressed in?

What information is presented in the question?

The calculation performed.

What is the question asking us to do?

Determine the number of significant figures the answer should be expressed to.

What strategies do we need in order to answer the question?

1. Determine the type of calculation being performed.
2. Count the number of significant figures based on the appropriate rules.
3. For multiplication and division, answers are expressed with as many significant figures as the number used with the least number of significant figures.

Answer

This is a division calculation, therefore the answer will be expressed to the lowest number of significant figures given. For this question, the reference number will be 1.3, which contains two significant figures.

Therefore, the answer will be expressed to two significant figures.

Sometimes numbers may be very large or very small, which means that it is much easier to express them using scientific notation (written as a decimal number multiplied by a power to the base of 10). The easiest way to do this is to:

- Move the decimal place in the number so that there is only one number to the left of the decimal point.
- Identify the number of significant figures required, and round the decimal number accordingly.
- Identify the number of times the decimal place has moved – this will be the exponent/power.

WORKED EXAMPLE 3

The diameter of the earth is approximately 12 742 km. Express this in scientific notation to three significant figures.

What information is presented in the question?

The diameter of the earth.

What is the question asking us to do?

Express the diameter of the earth to three significant figures using scientific notation.

What strategies do we need in order to answer the question?

1. Move the decimal place until there is only one number to the left of the decimal place.
2. Identify the number of significant figures required.
3. Write the answer in scientific notation.

Answer

By moving the decimal, we can have a new number of:

1.2 742.
= 1.2742

Considering we want to express the answer to three significant figures, our third significant figure will be seven. Since the fourth number is four, according to the rounding rules, our third significant figure will stay at seven.

Third significant figure → 1.2742 = 1.27

The number after 7 is less than 5, therefore our rounded number will be 1.27

Since we moved our decimal place four places to the left, our exponent/power will be four. Therefore the diameter can be expressed as:

1.27×10^4 km

4 ← Number of times the decimal point was moved

When examining other people's research, we can check for precision and accuracy by comparing the results obtained with other pieces of research, and also by comparing the results to what is expected. These expected results will be detected by studying the data obtained and will be represented in the results section of research.

PROGRESS QUESTIONS

Question 8

The value 15000.0 g contains

A. two significant figures.
B. five significant figures.
C. six significant figures.
D. seven significant figures.

Use the following information for questions 9–10.

The two following calculations were performed:

(1) 7.113 g + 0.64 g (2) 0.51 g × 1.996 mL

Question 9

Which of the following statements is true?

A. In calculation (1), the answer would be expressed to two decimal places.
B. In calculation (1), the answer would be expressed to five decimal places.
C. In calculation (1), the answer would be expressed to two significant figures.
D. In calculation (1), the answer would be expressed to five significant figures.

Question 10

Which of the following statements is true?

A. In calculation (2), the answer would be expressed to two significant figures.
B. In calculation (2), the answer would be expressed to three significant figures.
C. In calculation (2), the answer would be expressed to four significant figures.
D. In calculation (2), the answer would be expressed to five significant figures.

Limitations of data 4.3.14.1

There are factors that can limit the ability to conduct experiments.

What are some of the limitations when collecting data?

It is difficult to control every variable in an experiment. This limits the validity, accuracy and reproducibility of experimental results, making it sometimes difficult to identify the relationship between the independent and dependent variable. These limitations can be a result of the design and methodology of the experiment, or even from the surrounding environment. Access to relevant apparatus and reagents as well as the depth of understanding of the related field can also act as limitations to the research.

With respect to what we learn in VCE chemistry, most of the data in the Data Book was developed from experiments that were conducted under specific conditions. Therefore, the information presented is only true under those conditions. However, when conducting our own experiments in the classroom, the conditions are not the same and therefore the data we use may not exactly align with the information stated in the data book.

PROGRESS QUESTIONS

Question 11

Experiments are valid if

A. some variables are slightly adjusted throughout the experiment.

B. all variables are slightly adjusted throughout the experiment.

C. some variables outside the independent (and dependent) variable are controlled.

D. all variables outside the independent (and dependent) variable are controlled.

Theory summary

- There are many different types of errors that can affect the quality of scientific research.
- Each error has a different effect on the overall research.
  - Systematic error primarily affects precision of data.
  - Random error primarily affects accuracy of data.
- Accuracy and precision measure different aspects of quantitative data.
- Significant figures allude to the precision of experimental data. Data able to be expressed to a larger number of significant figures is generally considered to be more precise.
- The number of significant figures used to express answers depends on the mathematical operation being performed.
  - Multiplication and division: final answer is expressed to the lowest number of significant figures of a number used in the calculation.
  - Addition and subtraction: final answer is expressed to the lowest number of decimal places of a number used in the calculation.
- Repeatability and reproducibility all refer to the ability of the results to be obtained by repeating the experiment under the same or changed conditions.
- Resolution is the smallest change in quantity that is measurable (by a particular instrument).
- There will always be variables that limit research investigations.

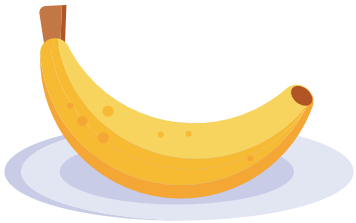
12D Questions

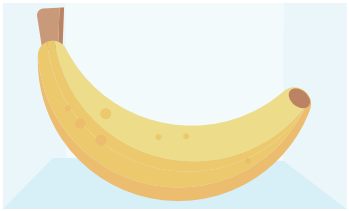
Mild Medium Spicy

Deconstructed

Use the following information to answer questions 12–14.

Ashley developed an experiment to identify the rate at which bananas ripen in an open area compared to in a closed area. To do so, they set up the following experiment.





Ashley measured the time it took, in hours, from peeling the banana to when the banana first started to turn brown. They checked the results every few hours during the day, but did not check it during the night.

Question 12 (1 MARK)

Which of the following steps will **not** improve the validity of the experiment?

A. Using bananas from the same bunch

B. Using the same type of bananas

C. Doing the experiment on a different day

D. Taking measurements at timed intervals

Question 13 (1 MARK)

Which of the following variables need(s) to be kept constant?

A. The size of the bananas

B. The temperature of the experiment

C. The timer used to measure the time

D. All of the above

Question 14 (4 MARKS)

Based on the results of the experiment, Ashley saw that the banana in the box began to ripen before the banana on the plate. Therefore, they concluded that bananas kept in a closed area ripen quicker than those left in an open environment. Comment on the validity of this conclusion.

Exam-style

Question 15 (4 MARKS)

For each of the descriptions, identify the type of error that has occurred.

Description	Type of error/mistake
Experimenter uses an uncalibrated thermometer to measure the heat of a reaction	
Some reagent falls off a measuring glass as a student walks back to the bench	
Student reads a measuring cylinder from the top of the meniscus	
Student uses the wrong reagent in a single reaction	

Question 16 (6 MARKS)

Ammonia is a strong cleaning agent found in many cleaning products. Depending on the purpose of the cleaner, different cleaners have different concentrations of ammonia. As part of an investigation to determine the concentration of ammonia, ammonia was reacted with different volumes of hydrochloric acid. It was expected that for every 20.00 mL of ammonia used, there would be 15.00 mL of hydrochloric acid required.

The results from the test are provided.

Test number	Volume of HCl reacted (mL)
1	18.80
2	19.00
3	14.75
4	18.85

a. Which group of 3 test results would be considered the most precise? 1 MARK

b. Are the results accurate or precise? Explain your reasoning. 4 MARKS

c. How many decimal places should the average titre of HCl, when calculated from the results obtained, be expressed to? 1 MARK

Question 17 (8 MARKS)

For their research investigation, a student wanted to conduct an experiment using a substance that is not commonly available in schools. As a consequence, they had to source a small sample from a nearby university.

a. Identify two limitations of the experiment. 2 MARKS

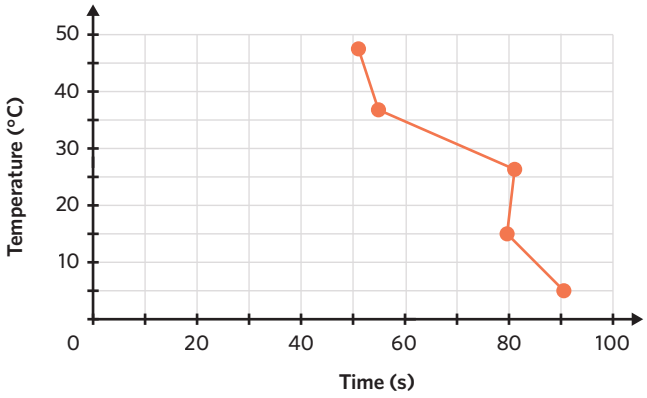
b. The student followed methodology presented by a research paper studying a similar question in the same field. Despite this, the results obtained in the experiment and the results reported by the researchers in the article were very different. Comment on the reproducibility of the results. 3 MARKS

c. Suggest a way in which the reproducibility can be improved. 1 MARK

d. What is the main difference between reproducibility and repeatability? 2 MARKS

Question 18 (1 MARK)

Consider the following graph.



Which of the following could **not** be used to describe the data point that was recorded at 25 °C?

A. Outlier

B. Systematic error

C. Random error

D. Mistake

Adapted from VCAA 2020 exam Short answer Q9

Question 19 (1 MARK)

Which of the following statements about conducting an experiment is most correct?

A. Precise results may be biased.

B. Accuracy is assured if sensitive instruments are used.

C. A method is valid if it identifies all controlled variables.

D. Repeating a procedure will remove the uncertainty of the results.

VCAA 2020 exam Multiple choice Q22

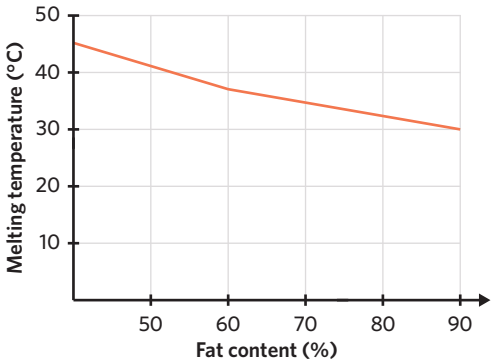
Question 20 (4 MARKS)

Balnea conducted an experiment to see how the fat content in chocolate affects the temperature at which the chocolate will melt.

a. Identify the independent variable. 1 MARK

b. Identify an appropriate control group for the experiment. 1 MARK

c. The results obtained were plotted on a graph as shown. What conclusion can be drawn from the results? 1 MARK



d. Balnea wanted to calculate the amount of fat present in the chocolate. To do so, 4.00 g samples of chocolate were required. What would be the maximum number of significant figures that the answer be expressed to? 1 MARK

Question 21 (4 MARKS)

Type 1 diabetes affects the body's ability to bring glucose into cells as there is not enough insulin. Insulin is responsible for helping to move glucose from the bloodstream to cells. This means that most of the sugar, which contains glucose, is not delivered to cells, and instead stays in the blood. Therefore, those with type 1 diabetes need to closely monitor their blood glucose levels.

The different sugar content in foods can affect blood glucose in different ways. Thomas wanted to test different foods and their effect on his blood glucose. As part of this test, he ate a variety of different snacks with different glucose contents and measured his blood glucose at baseline, and then every hour for four hours.

a. Identify the dependent variable. 1 MARK

b. Write an appropriate hypothesis for this research. 1 MARK

c. At the end of the test, Thomas decided to calibrate his glucose metre and realised that his metre was measuring values 0.20 mmol L^{-1} less than the true value. Identify how this would affect his results. 2 MARKS

12E Writing scientific material



How can the findings of scientific research papers be communicated?

Scientific investigations are often communicated using a large poster format. Models are used to display chemical understanding; however, they often have **limitations**. In this lesson, we will learn about how to share scientific information in a way that is easy to understand and that follows the conventions of scientific writing.

KEY TERMS AND DEFINITIONS

Limitations (models) often oversimplified, use approximations, and missing key details

STUDY DESIGN DOT POINTS

- conventions of scientific poster presentation, including succinct communication of the selected scientific investigation, and acknowledgements and references
- chemical concepts specific to the selected scientific investigation and their significance, including definitions of key terms
- conventions of science communication: scientific terminology and representations, symbols, formulas, standard abbreviations and units of measurement
- assumptions and limitations of investigation methodology and/or data generation and/or analysis methods

12A 12B 12C 12D 12E

- 4.3.7.2 & 4.3.7.3 Representing ideas with models & limitations of representations
- 4.3.13.2 & 4.3.16.1 Chemical terminology, conventions and abbreviations
- 4.3.13.3 Units of measurement in reports
- 4.3.15.1 Effective scientific communication

ESSENTIAL PRIOR KNOWLEDGE

12A Hypotheses

See question 102.

Representing ideas with models & limitations of representations 4.3.7.2 & 4.3.7.3

Chemical concepts can be represented visually and often do not show the complete picture.

How can limitations influence our understanding?

Models and figures can make it easy to understand the general idea of chemical concepts; however, they are sometimes unable to illustrate the idea in detail. For example, in the water cycle shown in figure 1, we can identify the major components in the process, but we cannot see what actually happens at each stage. The addition of the smaller details would make the model too complicated and hard to understand. Therefore, we need to understand that models are often used to summarise or demonstrate a particular idea, not to show all of the details involved in a concept.

These concepts, along with all of the other concepts covered in the chapter, allow us to both develop our own research as well as critique other experiments during our research journey. The outcome of this can be shown in the poster related to our water bottle experiment, as shown in figure 7.

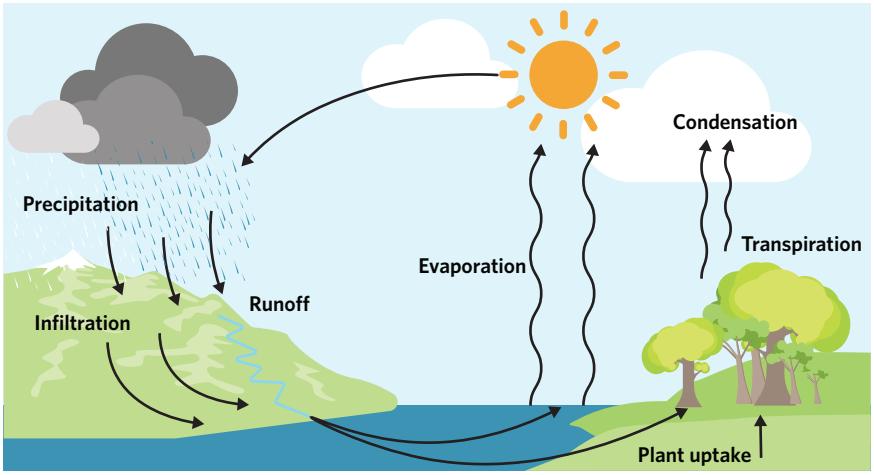


Figure 1 The water cycle

Why are models useful?

Models are often used to represent chemical concepts in a way that helps to make it easier to understand conceptual theory. Visual models are the most commonly used and perhaps most useful when conveying conceptual information. For example, the ball-and-stick model in figure 2 is a common representation of molecules and their bonds, and is often used in resources to demonstrate the complexities of chemical bonds.

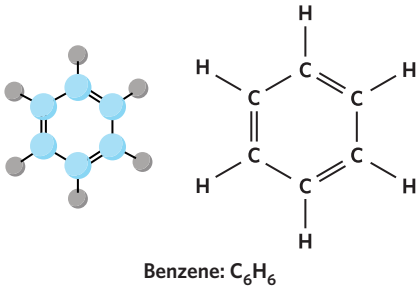


Figure 2 Chemical structures can be modelled in different ways.

Other visual representations include flow charts and diagrams such as the example in figure 1, which functions to summarise the overall steps involved in a process. Other commonly used visual representations include graphs and tables. Models do not just have to be visual, but can also be worded, or even formulaic. Chemical equations and formulas are also examples of models used in chemistry as they are different ways of representing concepts.

PROGRESS QUESTIONS

Question 1

Visual models generally cannot

A. include words.

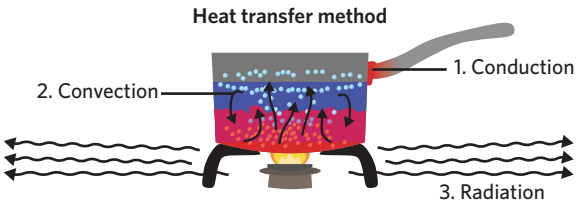
B. be made to scale.

C. be in three dimensions.

D. show all details related to a concept.

Question 2

The image provided shows the different ways in which heat can be transferred.



From this, we can see that

A. pure water boils at 100 °C.

B. metals conduct better than polymers.

C. there are three main types of heat transfer.

D. convection involves the transfer of heat through the movement of particles.

Chemical terminology, conventions and abbreviations 4.3.13.2 & 4.3.16.1

Chemistry has its own language when it comes to representing information.

How do we speak chemistry?

We know that chemistry has a particular language when presenting ideas. This includes the terms used, structural representations of chemicals, and symbolic representations of elements. The most recognisable example is the use of symbols to represent the names of the chemical elements, for example the use of the symbol O to represent the element oxygen. Other examples include:

- The use of subscripts and superscripts to represent multiples or charges of ions, e.g. NH_3 and Mg^{2+}
- The use of brackets in chemical and semi-structural formulas, e.g. $Mg(NO_3)_2$ and $CH_3CH_2CH(OH)CH_3$
- The use of variables/symbols to represent chemical concepts, e.g. N_A, n, and M
- Key terms representing multi-faceted chemical concepts, e.g. compound and molecule

Although there are certain terms and conventions that are used in different contexts, scientific concepts require specific conventions and terminology. Therefore, it is important that we select these according to the context. At times, scientific research will include an appendix that outlines the conventions and abbreviations relevant to the research that are not commonly used elsewhere.

It is also important for anything included in the research to be labelled appropriately. For example, tables and figures included in scientific writing all need to be accompanied by a table or figure legend and be referenced in the text. Furthermore, graphs need to be appropriately titled, with axis headings included with their appropriate units.

How are chemical reactions written?

An important part of chemistry is investigating chemical reactions. Chemical reactions involve the rearrangement of atoms found in the reactants to produce different products. This process is illustrated by a chemical equation as shown.

$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

Reactants → Products

Chemical equations show a lot of information about a chemical reaction as shown in figure 3.

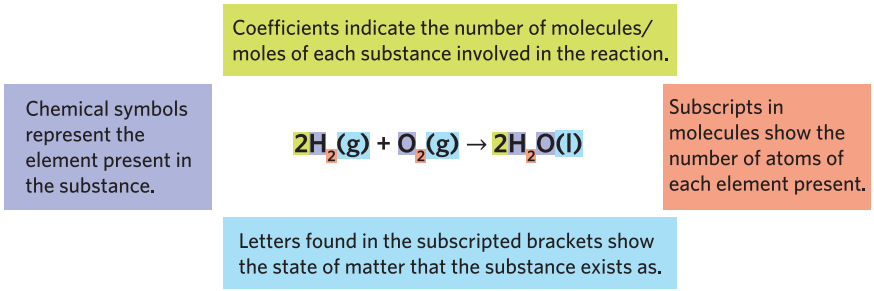


Figure 3 Key information found in a chemical equation

As we know, substances can exist in different states, each of which have their own convention when represented in a chemical reaction as shown in table 1.

Table 1 States of matter conventions

Convention	State
(g)	Gas
(s)	Solid
(l)	Pure liquid or pure molten liquid
(aq)	Aqueous (chemical species dissolved in water, also known as a solution)

USEFUL TIP

If there isn't a coefficient present, imagine that there is a 1 in front of the formula.

Another important component of a chemical equation is the use of coefficients in front of the formula of each substance. These numbers represent the ratio of the amounts of each of the substances present, and links to the mole concept. This is an important concept that we will continue to revisit throughout our studies.

In the chemical reaction shown, hydrogen gas reacts with oxygen gas to produce liquid water. The product (H_2O) formed is made from atoms that were present in the reactant molecules (H_2 and O_2). If we look even closer, we will notice that not only are the elements present in the reactants and products the same, but the number of atoms of each element is also the same on either side of the equation. When this is the case, we can say that the chemical equation is balanced. This highlights a concept known as the conservation of matter, whereby the total number and type of atoms in a system remains the same before and after a chemical change, where atoms are neither created nor destroyed.

$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

WORKED EXAMPLE 1

Balance the following chemical equation that represents the process of photosynthesis.

$CO_2(g) + H_2O(l) \rightarrow C_6H_{12}O_6(aq) + O_2(g)$

What information is presented in the question?

Unbalanced chemical equation for photosynthesis:

$CO_2(g) + H_2O(l) \rightarrow C_6H_{12}O_6(aq) + O_2(g)$

What is the question asking us to do?

Balance the chemical equation.

What strategies do we need in order to answer the question?

1. Determine the number of carbon, hydrogen and oxygen atoms on either side of the equation.
2. Change the number of atoms on either side of the equation by adding molecules where appropriate, which changes the coefficients in the equation.

Answer

Initially, there is one carbon atom, two hydrogen atoms, and three oxygen atoms on the reactants side of the equation and six carbon atoms, 12 hydrogen atoms, and eight oxygen atoms on the products side of the equation.

In order to balance the carbon atoms, we need a total of six CO_2 molecules:

$6CO_2(g) + H_2O(l) \rightarrow C_6H_{12}O_6(aq) + O_2(g)$

There are now:

Reactant : Products

6 carbon atoms : 6 carbon atoms

13 oxygen atoms : 8 oxygen atoms

2 hydrogen atoms : 12 hydrogen atoms

In order to balance the hydrogen atoms, we need six H_2O molecules:

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + O_2(g)$

There are now:

Reactant : Product

6 carbon atoms : 6 carbon atoms

18 oxygen atoms : 8 oxygen atoms

12 hydrogen atoms : 12 hydrogen atoms

In order to balance the oxygen atoms, we need six O_2 molecules:

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

There are now:

Reactant : Product

6 carbon atoms : 6 carbon atoms

18 oxygen atoms : 18 oxygen atoms

12 hydrogen atoms : 12 hydrogen atoms

The equation is now balanced.

The numbers in front of the molecular formulas indicate the ratio of different molecules reacting. In this case, six molecules of CO_2 react with six molecules of H_2O to form one molecule of $C_6H_{12}O_6$ and six molecules of O_2.

Given that balanced chemical equations represent the number of molecules required in a reaction and the number of molecules produced in a reaction, they also represent mole ratios. If we recall from VCE chemistry Units 1 & 2, the mole is a unit which represents a fixed number of molecules/atoms (Avogadro's number). Therefore, using the balanced equation from the worked example above, the mole ratio is:

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$

$CO_2 : H_2O : C_6H_{12}O_6 : O_2$

6 : 6 : 1 : 6

This means that six mol of CO_2 reacts with six mol of H_2O to produce one mol of $C_6H_{12}O_6$ and six mol of O_2. Based on this ratio, we can calculate the amount required for a specific reaction to occur, or the amount of product formed. The general formula to perform these calculations is:

$$n(\text{unknown}) = \frac{\text{WANT}}{\text{KNOW}} \times n(\text{known}),$$

where WANT is the coefficient or number in front of the chemical species whose amount we want to determine and KNOW is the coefficient or number in front of the chemical species whose amount we know. Using the example above, we can now determine the amount of $C_6H_{12}O_6(aq)$ produced. For example, if one mol of $CO_2(g)$ reacts with sufficient $H_2O(l)$, 0.17 mol of $C_6H_{12}O_6$ will be produced as shown in figure 4.

KNOW WANT

$$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$$

$$n(C_6H_{12}O_6) = \frac{1}{6} \times 1 \text{ mol} = 0.17 \text{ mol}$$

Figure 4 Steps to determine the amount of an unknown substance from a substance where the amount is known

USEFUL TIP

When balancing complicated equations, it may be easier to start by balancing key elements: those that are only found in one product.

PROGRESS QUESTIONS

Question 3

Chemical terminology is used to describe

A. a single idea only.

B. a multi-process concept only.

C. both a multi-process concept and single ideas.

D. neither a multi-process concept nor single ideas.

Units of measurement in reports 4.3.13.3

Different units are used to represent different measurements.

Why are units so important in chemistry?

In VCE chemistry, we work with various different types of data ranging from amount, mass, volume, and temperature, all of which are measured in different units. Table 2 shows some common units that can be found in the VCE Data Book.

Table 2 Common units used in chemistry as outlined by the VCE Data Book

Name	Symbol	Value
Avogadro constant	N_A or L	6.02×10^{23} mol^{-1}
Charge on one electron (elementary charge)	e	-1.60×10^{-19} C
Faraday constant	F	96 500 C mol^{-1}
Molar gas constant	R	8.31 J mol^{-1} K^{-1}
Molar volume of an ideal gas at SLC (25 °C and 100 kPa)	V_m	24.8 L mol^{-1}
Specific heat capacity of water	c	4.18 kJ kg^{-1} K^{-1} or 4.18 J g^{-1} K^{-1}
Density of water at 25 °C	d	997 kg m^{-3} or 0.997 g mL^{-1}

This is not a complete list of all of the units that we will use. The units used will depend on the type of information that we are collecting and trying to convey, meaning they vary contextually.

PROGRESS QUESTIONS

Question 4

Units

A. can be used to represent multiple different concepts.

B. are not found in the VCE chemistry Data Book.

C. do not need to be included in calculations.

D. like kilograms can be multiplied by grams in a calculation.

Question 5

The most suitable unit to measure volume would be

A. minutes.

B. centimetres.

C. faradays.

D. litres.

Effective scientific communication 4.3.15.1

Scientific communication is part of the scientific process (figure 5) and needs to be concise.

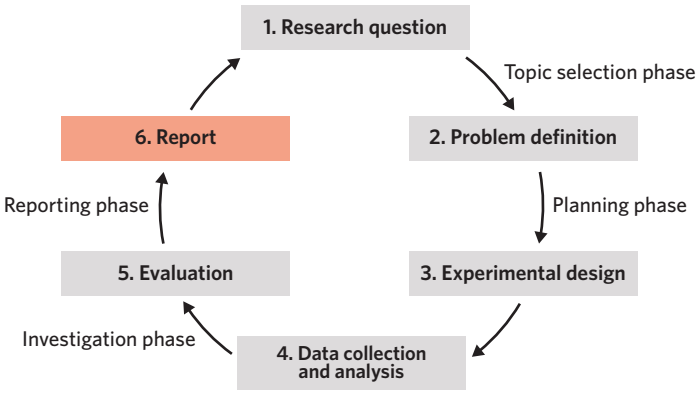


Figure 5 A scientific process

How can we communicate concisely in a poster?

The purpose of scientific articles and reports is to be able to convey a finding or message to the reader. Therefore, it is important to be concise and clear in the way we represent information without being verbose. Getting to the point is more important than sounding sophisticated. Some key techniques for effective communication in science include:

- use of short sentences that get to the point
- consistent voice
- maintaining a neutral stance and tone by avoiding subjective language
- use of visuals to support writing where necessary
- reference to related theory.

Another important factor to consider when communicating scientific ideas, especially in a research article, is the appropriate formatting of the main text as well as any references used. For example, scientific research is written in a particular order with predetermined sections as shown in figure 6.

The different sections of the poster convey different types of information, and together they provide a deeper understanding of an idea. Based on figure 6, we can see that a very important part of the poster is the discussion section. In fact, this is quite common in any scientific writing as this is the section where we bring all of the data and ideas together. The discussion section gives us an opportunity to elaborate on and explain the results, and to show how the research and its results contributes to the pool of knowledge relating to the same or similar ideas. Regardless of whether or not the results support the hypothesis, the analysis of the results and what they mean is the main purpose of the discussion. From this analysis, we are able to identify any future implications of the experiment.

We can now use everything that we have written about to provide a conclusion for the research. Similar to an essay, the conclusion is a very brief summary of what was found in the experiment.

Understanding that scientific ideas are built upon previous research, it is important to acknowledge the source of the information that formed the basis of the research. Depending on where scientific work is submitted to, the referencing requirements may vary. For example, some publications require references to be done in Harvard style, whereas others may require APA style. Information about the exact formatting required is available online.

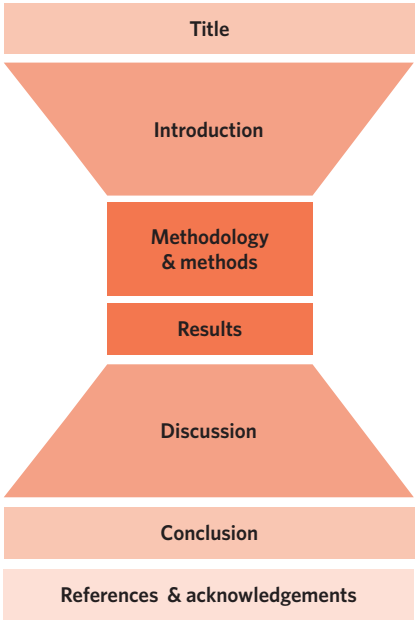


Figure 6 Outline of a scientific report

BPA SCIENTIFIC INQUIRY



When we put this into the context of the water bottle experiment, we can develop a scientific poster to share our experiment as seen in figure 7.

PROGRESS QUESTIONS

Question 6

Scientific writing is supposed to be

A. simple and clear.

B. verbose and sophisticated.

C. complex and difficult to understand.

D. only accessible to readers with degrees.

Question 7

A scientific report must include

A. data.

B. diagrams.

C. a discovery.

D. a revelation.

Theory summary

- Chemical concepts can be represented visually, however, these can be limited in their ability to show the idea in great detail.
- The units of measurement used depend on the type of information that is being collected.
- Different concepts contain different terminology and conventions.
- Being clear and concise is important when communicating scientific ideas.

Is it dangerous to drink water from a plastic water bottle that has been left in a warm environment?

INTRODUCTION

Bisphenol A (BPA), as shown in figure 7.1, is a monomer, a small building block, used to produce a strong plastic polymer known as polycarbonate (Vogel, 2009). Due to its widespread uses in bottles and containers, there is growing concern over the health effects of using BPA in household plastic items.

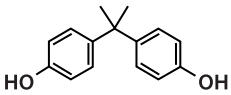


Figure 7.1 Structure of a bisphenol A

In water-containing products such as drink bottles, BPA is known to leach when hydrolysed by heat, pH, or microwaves into the water over time (Le *et al*. 2008). When consumed, this can result in the disruption of important hormone-driven processes in the body (Diamanti-Kandarakis *et al*., 2009).

This experiment aims to test the effect of temperature on the release of BPA into water. It is expected that if the breakdown of BPA from plastic depends on the temperature of the surrounding environment, then an increase in temperature would result in an increase in the concentration of BPA found in the water.

METHODOLOGY AND METHODS

- 3 × 600 mL unopened BPA-containing bottles of water (from the brand Rolo Water)
- 3 × 600 mL unopened bottles of water in a BPA-free plastic bottle (from the brand Rolo Water)
- HPLC machine with 0.50 ng mL^{-1}, 1.0 ng mL^{-1}, 1.5 ng mL^{-1}, and 2.0 ng mL^{-1} BPA standards
- Micropipette, pipette tips, fridge, and an incubator

Part A: Identification of the retention time of BPA.

1. Inject a 5 µL sample of a 2.0 ng mL^{-1} BPA standard into the HPLC machine.
2. Record the retention time of the most prevalent peak.
3. Repeat steps 1 and 2 with a fresh sample of the same standard.

Part B: Development of the BPA calibration curve (figure 7.2).

1. Inject a 5 µL sample of 0.50 ng mL^{-1} BPA standard through the HPLC machine.
2. Record the area under the peak for the sample.
3. Repeat steps 1–2 for the other standards.

Part C: Determination of the concentration of BPA.

1. Label each BPA-containing bottle A, B and C, and each BPA-free bottle D, E and F.
2. Place bottles A and D in a fridge at 4 °C.
3. Place bottles B and E in an incubator set at 20 °C.
4. Place bottles C and F in an incubator set at 30 °C.
5. Leave the samples for 2 hours.
6. After the 2 hour period, inject a 5 µL sample of water from bottle A into the HPLC machine using the micropipette.
7. Record the area under the peak for sample A at the retention time determined for BPA in Part A.
8. Repeat steps 6 and 7 for bottles B–F.

'Although BPA was found in very small concentrations in water from non-BPA bottles, the concentration of BPA found in water from BPA bottles does increase as the temperature of the water increases.'

Figure 7 Water bottle experiment scientific poster

RESULTS

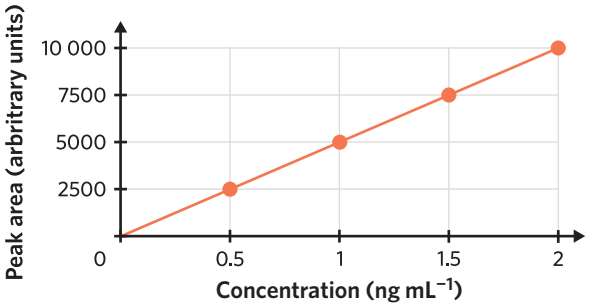


Figure 7.2 Calibration curve of known standards of BPA

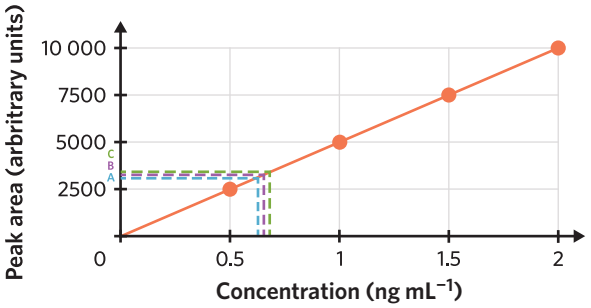


Figure 7.3 Determination of the concentration of BPA in samples A–F

Table 7.1 Concentration of BPA in each sample

Sample	Peak Area (arbitrary units)	Concentration (ng mL^{-1})
A BPA bottle at 4 °C	2610	0.58
B BPA bottle at 20 °C	2720	0.61
C BPA bottle at 30 °C	2830	0.63
D BPA-free bottle at 4 °C	101	0.022
E BPA-free bottle at 20 °C	100	0.022
F BPA-free bottle at 30 °C	101	0.022

DISCUSSION

Compared to control samples D–F (Table 7.1) in which water was placed in a BPA-free bottle, the presence of BPA in the water bottles resulted in a greater concentration of BPA in the water samples. For samples A–C, it can be seen that an increase in temperature (figure 7.3) is correlated with an increase in the concentration of BPA measured (0.58, 0.61, and 0.63 ng mL^{-1} respectively).

BPA can be released into the contents of water bottles when the plastic begins to degrade (Biedermann-Brem & Grob., 2008). In particular, an increase in temperature results in the increase in the rate at which the plastics are degraded. This trend is shown in the results of this experiment.

CONCLUSION

In the same amount of time, an increase in temperature results in a slight increase in the concentration of BPA found in water of BPA-containing water bottles. BPA is therefore more soluble in water at higher temperatures.

Future implications - as BPA is found in a number of different plastic materials, the results of this experiment can help consumers make more informed decisions about the way they currently store goods.

Limitations - as there are so many different types of plastics available, the results of the study are specific to only Rolo Water.

REFERENCES AND ACKNOWLEDGEMENTS

Biedermann-Brem, S., Grob, K. (2009). Release of bisphenol A from polycarbonate baby bottles: water hardness as the most relevant factor. *Eur. Food. Res. Technol.*, 228, 679–684.

Diamanti-Kandarakis, E., Bourguignon, J. P., Giudice, L. C., Hauser, R., Prins, G. S., Soto, A. M., Zoeller, R. T., & Gore, A. C. (2009). Endocrine-disrupting chemicals: an Endocrine Society scientific statement. *Endocrine reviews, 30*(4), 293–342.

Le, H. H., Carlson, E. M., Chua, J. P., & Belcher, S. M. (2008). Bisphenol A is released from polycarbonate drinking bottles and mimics the neurotoxic actions of estrogen in developing cerebellar neurons. *Toxicology letters, 176*(2), 149–156.

Vogel S. A. (2009). The politics of plastics: the making and unmaking of bisphenol a "safety". *American journal of public health, 99*(3), 559–566.

600 words ±10% (excluding titles, figures and references) = 641

12E Questions

Mild Medium Spicy

Deconstructed

Use the following information to answer questions 8–10.

The following are excerpts from an article titled 'What is a virus? How do they spread?'.

Are viruses alive?

Viruses rely on the cells of other organisms to survive and reproduce, because they can't capture or store energy themselves. In other words they cannot function outside a host organism, which is why they are often regarded as non-living.

Outside a cell, a virus wraps itself up into an independent particle called a virion. The virion can "survive" in the environment for a certain period of time, which means it remains structurally intact and is capable of infecting a suitable organism if one comes into contact.

How do viruses spread?

Once a person is infected with a virus, their body becomes a reservoir of virus particles which can be released in bodily fluids – such as by coughing and sneezing – or by shedding skin or in some cases even touching surfaces.

The virus particles may then either end up on a new potential host or an inanimate object. These contaminated objects are known as fomites, and can play an important role in the spread of disease.

Source: Tajouri, L. (2020). What is a virus? How do they spread? How do they make us sick? The Conversation. theconversation.com/what-is-a-virus-how-do-they-spread-how-do-they-make-us-sick-133437

Question 8 (1 MARK)

The style of scientific writing above can be described as being

A. lacking in detail.

B. clear.

C. quantitative.

D. basic.

Question 9 (1 MARK)

Which of the following terms used in the article could be considered as a science-specific term related to viruses?

A. Non-living

B. Reservoir

C. Virion

D. Contaminated

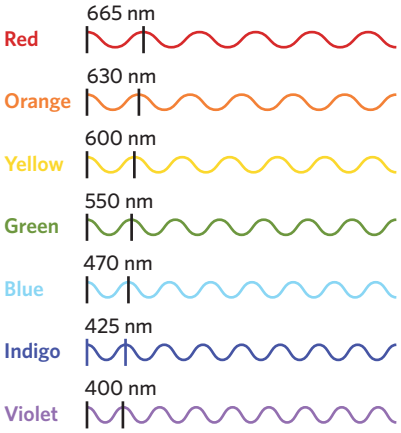
Question 10 (3 MARKS)

Construct a visual model to show the process of how a handshake can help spread viruses.

Exam-style

Question 11 (3 MARKS)

The light that we see is a combination of different colours.



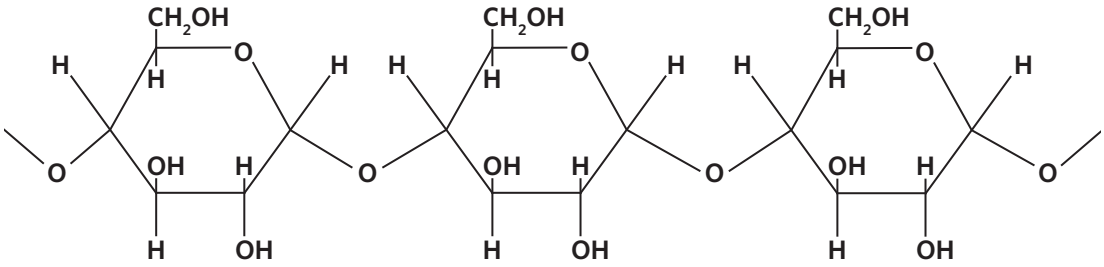
a. What is the main message conveyed by the visual model provided? 1 MARK

b. What is the unit of measurement used to measure the wavelength of light? 1 MARK

c. Identify the main limitation with this visual representation. 1 MARK

Question 12 (1 MARK)

The chemical formula shown is a small section of a sugar molecule. Give one limitation of this model.



Question 13 (1 MARK)

Which of the following is **not** a unit of measurement commonly used in calculations in VCE chemistry?

A. L **B.** M **C.** N **D.** K

Question 14 (3 MARKS)

Olaf wanted to conduct an experiment to see the effect of sunlight on the rate of growth of carrots.
The results of the experiment are shown with the units for length of sun exposure omitted.

Test	Length of sun exposure	Length of carrot (cm)
A	0	0.15
B	1	15
C	2	24
D	3	29

a. Identify the most appropriate unit for the data relating to the length of sun exposure. 1 MARK

b. Which of the tests would be considered as the control group? 1 MARK

c. Identify the dependent variable. 1 MARK

Question 15 🌶🌶🌶 (3 MARKS)

Medusa received a crystal growing kit as a gift and wanted to figure out how to grow the largest crystals possible. The instructions for the kit are as follows:

1. Add boiling water to a crystal growing tray.
2. Stir mixture until everything is dissolved.
3. Place rocks found in the kit at the bottom of the tray.

The kit contained multiple different sized rocks that could be used to make crystals. The three crystal mixtures included in the kit were identical.

a. Identify the independent variable. 1 MARK

b. Write an appropriate aim for the experiment. 1 MARK

c. Medusa wanted to write a poster to share the findings with other classmates. As part of this, outline the main sections that must be included in the poster. 1 MARK

Chapter 12 review

Multiple choice (15 MARKS)

Use the following information to answer questions 1–2.

Dean conducted an observational experiment to determine people's emotional response to the use of face masks.

Question 1 (1 MARK)

The data collected would be considered

A. qualitative data.
B. quantitative data.
C. descriptive data.
D. concrete data.

Question 2 (1 MARK)

The following conclusion was drawn from the results obtained:

'As the use of face masks increased, the happiness of people decreased.'

The relationship between the use of face masks and happiness can be described as being

A. causal.
B. correlated.
C. unrelated.
D. captivated.

Question 3 (1 MARK)

Scientific posters communicate the findings of scientific investigations.

Which section of a scientific poster should explain the reason for undertaking an investigation?

A. Discussion
B. Conclusion
C. Introduction
D. Methodology

VCAA 2022 exam Multiple choice Q1

Question 4 (1 MARK)

A solvent has the following risk statement printed on its label.

'Inhalation of fumes may cause dizziness.'

To minimise the risk associated with the effects of exposure when using this solvent, a student should

A. use gloves.
B. wear a laboratory coat.
C. keep the solvent away from flames.
D. use the solvent in a well-ventilated area.

VCAA 2012 Exam 2 Multiple choice Q1

Question 5 (1 MARK)

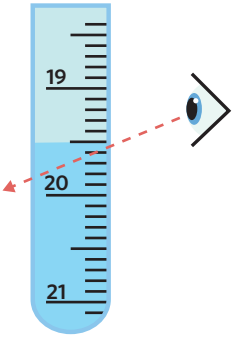
The purpose of a control is to

I. improve the accuracy of results.
II. improve the validity of results.
III. show that any changes were due to the independent variable.

A. 1 only
B. 3 only
C. 2 and 3 only
D. 2 only

Question 6 (1 MARK)

The error illustrated by the diagram would have the greatest effect on



A. the precision of results.
B. the accuracy of results.
C. the repeatability of an experiment.
D. the conclusion of an experiment.

Question 7 (1 MARK)

Which of the following is not considered to be a limitation?

A. Access to appropriate reagents
B. Misinterpretation of the methodology
C. Access to information
D. Relatively new field of research

Question 8 (1 MARK)

According to the SDS provided, the substance is dangerous as it is

Hazards	
SDS	External SDS
R-phrase	R11, R36, R66, R67
S-phrase	S16, S26, S33
Main hazards	Flammable (F) Irritant (Xi)
NFPA 704	

A. considered 3 on the Richter scale.
B. really heavy.
C. able to freeze easily.
D. an irritant.

Question 9 (1 MARK)

Forgetting to perform a step outlined in the methodology of an experiment is best described as

A. a systematic error.
B. an obstructive error.
C. a random error.
D. bias.

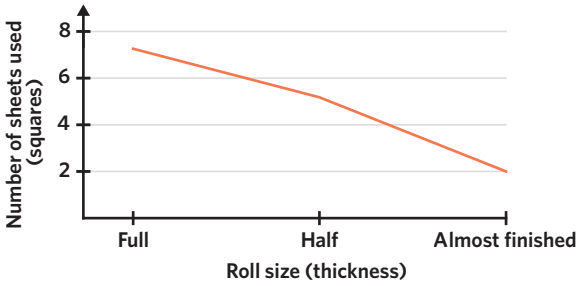
Question 10 (1 MARK)

At a training session one day, Anthony measured the time it took him to run 400 m.
The controlled variables in this experiment would include

A. the timer used, trial times, and the shoes worn.
B. the time recorded, the running route, and the apparel worn.
C. the distance, the running route, and the rest period.
D. the water intake, the rest period, and his pace.

Question 11 (1 MARK)

From the graph provided, it can be seen that



A. the number of sheets of paper used is constant.

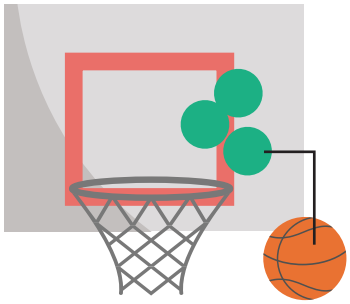
B. the number of sheets used increases as the size of roll decreases.

C. the larger the roll, the fewer sheets used.

D. the smaller the roll, the fewer sheets used.

Question 12 (1 MARK)

Kat was practising her basketball shots and used green paint to map each of her three shots.



Based on the results, her shooting can be described as being

A. accurate but not precise.

B. precise but not accurate.

C. both precise and accurate.

D. neither accurate nor precise.

Question 13 (1 MARK)

Scientists often repeat trials of an experiment using the same experimental method and the same equipment. Which one attribute of experimental data could be improved when there is an increase in the number of times that a trial is repeated?

A. Bias

B. Validity

C. Accuracy

D. Precision

Adapted from VCAA 2022 exam Multiple choice Q5

Question 14 (1 MARK)

Which one of the following statements about conducting an experiment is the most correct?

A. Precise results may be biased.

B. Accuracy is assured if sensitive instruments are used.

C. A method is valid if it identifies all controlled variables.

D. Repeating a procedure will remove the uncertainty of the results.

VCAA 2019 exam Multiple choice Q22

Question 15 (1 MARK)

Before water treatment authorities release water into the environment, the water is tested to ensure it is safe and meets environmental standards. The concentration of organic carbon is one indicator of water quality. In an experiment, a student determines the concentration of organic carbon by conducting a redox titration between the organic carbon in a water sample and standard acidified potassium permanganate solution, $KMnO_4$.

To accurately determine the concentration of organic carbon, an action the student should take is to

A. collect samples before and after a storm.

B. repeat the titration using a different standard solution.

C. use a measuring cylinder to measure the volumes of water samples.

D. rinse the burette with deionised water before filling it with the standard acidified $KMnO_4$ solution.

VCAA (NHT) 2018 exam Multiple choice Q9

Short answer (35 MARKS)

Question 16 (4 MARKS)

Oobleck is a substance that is unusual. As a liquid, it can be easily poured. However, when there is a force acting on it, it behaves like a solid. Oobleck is easy to make and consists of cornflour and water. Shuka wanted to test the effect of the mass of cornflour on the 'hardness' of the oobleck.

a. Identify the independent variable. 1 MARK

b. What type of data is being collected in this experiment? 1 MARK

c. As part of the experiment, Shuka tested the hypothesis using the following samples:

Sample 1	Sample 2	Sample 3
1.0 g cornflour + 100 mL of water	2.0 g of cornflour + 200 mL of water	3.0 g of cornflour and 300 mL of water

Comment on the validity of the experiment. 2 MARKS

Question 17 (6 MARKS)

To reduce the impact of diet-related diseases, researchers have tried to develop and suggest a taxation system that helps Australians to become healthier. The model that the researchers developed and plan to test is shown.

Intervention	Tax or subsidy	Sources of assumptions
Saturated fat tax	\$1.37/100 g of saturated fat	Tax on saturated fat content in foods with > 2.3% saturated fat, excluding drinking milk
Excess salt tax	\$0.30/1 g of sodium	Tax on sodium in excess of Australian maximum recommended levels, excluding fresh fruits, vegetables, meats and dairy products
Sugar-sweetened beverage tax	\$0.47/L	Tax on sugar-sweetened soft drinks, energy drinks, cordials, and fruit drinks
Sugar tax	\$0.94/100 mL of ice cream; \$0.85/100 g of sugar	Tax on ice cream containing > 10 g of sugar per 100 g of ice cream; tax on sugar content in excess of 10 g per 100 g of all other products, excluding fresh fruits, vegetables and unflavoured dairy products

Table: doi: 10.1371/journal.pmed.1002232.t001

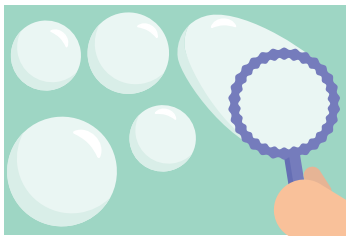
a. Write a hypothesis for this experiment. 1 MARK

b. Suggest what effect this tax system would have on food consumption. 2 MARKS

c. What are the main concerns related to this system? 3 MARKS

Question 18 (9 MARKS)

Jasper loves playing with bubbles. After running out of his bubble solution, he decided to develop a solution that would make the largest bubbles.



After conducting research, Jasper realised that bubble solutions are made from different substances and water. Therefore, he decided to test three different solutions containing dishwashing detergent, glycerin and corn syrup.

Method

1. Add 5 mL of dishwashing detergent to 200 mL of water.
2. Stir solution.
3. Place the bubble wand into the solution for 3 seconds.
4. Pull the bubble wand out of the solution and wave the hand once to make bubbles.
5. Take a photo of the bubbles formed.
6. Measure the diameter of the largest bubble in the photo.
7. Repeat for glycerin and corn syrup.

a. Identify an appropriate control for this experiment. 1 MARK

b. The results of the experiment are shown.

	Diameter of the largest bubble (cm)			
Substance	**Test 1**	**Test 2**	**Test 3**	**Average**
Dishwashing detergent	5	4.8	3	4.3
Glycerin	7.1	7.2	7	7.1
Corn syrup	7.5	7.6	7.5	7.5

i. Would a bar graph, column graph or line graph be most suitable to represent the results shown in the table? 1 MARK

ii. Which substance gave the most precise results? 1 MARK

iii. Comment on the reproducibility of the results. 5 MARKS

iv. Based on the data, what can be concluded about the experiment? 1 MARK

Question 19 (8 MARKS)

Scientist Émilie du Châtelet proposed a law stating that energy cannot be created or destroyed; it can only be transformed or transferred. This principle is still believed to be true to this day.

a. Consider the scenario shown, involving the use of a coal barbecue to cook food. Based on this scenario, a student made the following statement about the law of conservation of energy: 'Energy can be lost because the chemical energy that was available in the coal was used to start a fire to cook food. However, some of the heat escaped the barbecue and was not able to be used to cook the food.' Comment on the accuracy of the statement made. 4 MARKS



b. To test the theory, the student wanted to develop an experiment that could measure the energy in the coal, the barbecue, the food and the air to see if the total amount of energy would be the same.

i. Identify a limitation of the experiment. 1 MARK

ii. List 3 variables that would need to be controlled. 3 MARKS

Question 20 🌶🌶🌶 (8 MARKS)

The taste buds on our tongue are sensitive to different tastes. The amount of food required to 'taste' something can vary between people, but can also be trained. For example, we can train our taste buds to increase the threshold of sourness that we can handle before we register the sour taste by consuming foods with a high sourness rating.

In an experiment to test this hypothesis, researchers wanted to find out whether or not having subjects consume varying concentrations of vinegar prior to eating a piece of lemon would reduce a person's reaction to consuming the lemon.

a. Identify the independent variable. 1 MARK

b. To measure the response of a person to consuming the lemon, the experiment measured both facial expressions and a self-rating score of one to five, where five corresponded to 'very sour'. The results of the experiment are shown.

Concentration of vinegar (M)	1.0	2.0	3.0	4.0
Facial expression				
Self rating	3	2	4	4

i. Describe a key ethical concern in this experiment. 2 MARKS

ii. Comment on the validity of the experiment. 4 MARKS

iii. What conclusion can be drawn from the experiment? 1 MARK

Back to contents

ESSENTIAL PRIOR KNOWLEDGE

Questions and answers

These questions are designed to quickly break down any misconceptions and alert us to any knowledge that is 'essential' to understanding the coming lesson's content. There is one question for each Essential prior knowledge dot point on the lesson's first page.

Image: Pablolog42/Shutterstock.com

Essential prior knowledge questions

1A Fossil fuels

Question 1

A molecule can be represented by the following formula

A. Ag

B. H_2

C. Na_4XeO_6

D. NaCl

Question 2

Which of the following is not classified as a hydrocarbon?

A. Methane

B. Octane

C. Nonanol

D. Ethene

Question 3

Another chemical term for combustion is

A. oxidation.

B. reduction.

C. burning.

D. ignition.

1B Biofuels

Question 4

The term non-renewable fossil fuel is concerned mainly with the

A. rate of usage.

B. time taken to replace it.

C. amount of plant decomposition.

D. use of nuclear energy.

1C Fuel for the body

Question 5

Polymers are made up of repeating units called

A. dimers.

B. isomers.

C. monomers.

D. centromeres.

Question 6

Which of the following does not represent an oxidation reaction?

A. $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$

B. $2Ca(s) + O_2(g) \rightarrow 2CaO(s)$

C. $CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(l)$

D. $NaCl(aq) + KOH(aq) \rightarrow KCl(aq) + H_2O(l)$

1D Enthalpy changes and combustion reactions

Question 7

What is an electrostatic attraction when referring to chemical bonding?

A. Attraction between protons and neutrons

B. Repulsion between protons and neutrons

C. Attraction between protons and electrons

D. Repulsion between protons and electrons

Question 8

Which of the following statements is/are true?

A. Energy is released as chemical bonds are formed

B. The formation of chemical bonds makes particles more stable

C. Energy is required to break chemical bonds to overcome electrostatic attraction between particles

D. All of the above

Question 9

Consider the following reaction where 1 mole of oxygen gas and 2 moles of hydrogen gas are reacted to produce two moles of water.

$O_2(g) + 2H_2(g) \rightarrow 2H_2O(l)$

Which combination of reactants would produce 4 moles of water?

A. $2O_2(g) + 4H_2(g)$

B. $2O_2(g) + 2H_2(g)$

C. $O_2(g) + 4H_2(g)$

D. $O_2(g) + 2H_2(g)$

2A Calculating energy changes from combustion reactions

Question 10

The following is a combustion reaction equation for methanol.

$2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$

For every 1 mole of methanol that reacts, how many moles of oxygen gas are required?

A. 1 mole

B. 3 moles

C. $\frac{3}{2}$ moles

D. $\frac{2}{3}$ moles

Question 11

The volume occupied by 1 mole of an ideal gas at constant temperature and pressure

A. depends on the molecular mass of the gas.

B. depends on the size of the gas molecules.

C. depends on the number of gas particles.

D. is always the same.

Question 12

Which of the following represents a thermochemical equation for a combustion reaction?

A. $2H_2O(l) \rightarrow O_2(g) + 2H_2(g), \Delta H = +572$ kJ

B. $CH_3OH(l) + \frac{3}{2}O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

C. $C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$, $\Delta H = -1560$ kJ mol^{-1}

D. $Cu^{2+}(aq) + 2OH^-(aq) \rightarrow Cu(OH)_2(s)$

2B Calculating energy changes using water

Question 13

Methanol combusts according to the thermochemical equation.

$CH_3OH(l) + \frac{3}{2}O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

$\Delta H = -726$ kJ mol^{-1}

How much energy is released in the combustion of 1.00 g of methanol?

A. 22.7 kJ

B. 23.2 kJ

C. 32.0 kJ

D. 726 kJ

2C Energy from fuels and food

Question 14

Which of the following **cannot** be used as a source of energy by humans?

A. Carbohydrates

B. Caffeine

C. Protein

D. Fat

Question 15

In an experiment, a given mass of propane is combusted, causing 200.0 g of water to increase in temperature by 6.40 °C. The amount of energy absorbed by water is

A. 1280 J

B. 1280 kJ

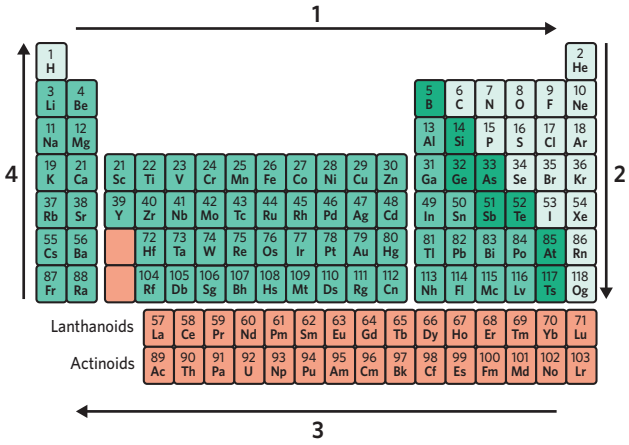
C. 5350 J

D. 5350 kJ

3A Redox reactions

Question 16

Electronegativity describes how strongly an atom attracts electrons towards itself. Consider the following annotated periodic table. Which two arrows show how electronegativity increases along periods and down groups in the periodic table.



A. Arrows 1 and 2

B. Arrows 2 and 3

C. Arrows 3 and 4

D. Arrows 1 and 4

Question 17

When exposed to oxygen in the air, a reactive metal will

A. gain electrons and form a metal hydroxide.

B. lose electrons and form a metal hydroxide.

C. gain electrons and form a metal oxide.

D. lose electrons and form a metal oxide.

3B Writing redox equations

Question 18

Consider the following acid-base reaction, where X denotes an unknown species?

$H^+(aq) + OH^-(aq) \rightarrow X$

Which species is represented by X?

A. $H_2O_2(aq)$

B. $H_2O(aq)$

C. $H_2O_2(l)$

D. $H_2O(l)$

Question 19

Which of the following correctly classifies the species undergoing oxidation and reduction in the following reaction?

$Cu(s) + NO_3^-(aq) \rightarrow NO(g) + Cu^{2+}(aq)$

	Oxidation	Reduction
A.	$Cu(s)$	$NO_3^-(aq)$
B.	$Cu^{2+}(aq)$	$NO(g)$
C.	$NO_3^-(aq)$	$Cu(s)$
D.	$NO(g)$	$Cu^{2+}(aq)$

3C Primary galvanic cells

Question 20

Graphite and diamond are both carbon allotropes.
What is one difference between graphite and diamond?

A. Graphite is conductive and diamond is non-conductive.

B. Diamond is conductive and graphite is non-conductive.

C. Diamond is made of 2D sheets and graphite has a 3D crystalline structure.

D. Diamond contains free electrons and graphite does not.

Question 21

How does charge flow through a wire in an electrical circuit?

A. Anions flow from an area of positive charge to an area of negative charge.

B. Electrons flow from an area of negative charge to an area of positive charge.

C. Cations flow from an area of negative charge to an area of positive charge.

D. Protons flow from an area of positive charge to an area of negative charge.

3D Designing galvanic cells

Question 22

Which of the following is a correct statement about the reactivity of zinc and cobalt under standard conditions?

A. $Zn(s)$ is a stronger reducing agent than $Co(s)$.

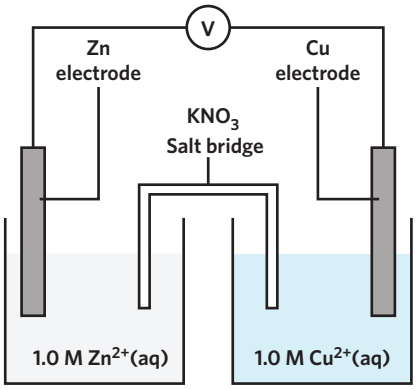
B. $Co(s)$ is a stronger reducing agent than $Zn(s)$.

C. A redox reaction is feasible between $Co(s)$ and $Zn(s)$

D. A redox reaction is feasible between $Co^{2+}(aq)$ and $Zn^{2+}(aq)$

Question 23

The Daniell cell, a type of galvanic cell, was first constructed in the mid–1800s, and this type of cell is still in use today. A diagram of the Daniell cell is shown.



Which of the following options correctly describes the $Zn(s)$ electrode?

A. Positive cathode

B. Positive anode

C. Negative cathode

D. Negative anode

3E Fuel cells

Question 24

An unbalanced oxidation half-equation is given.

$C_2H_5OH \rightarrow CO_2$

Which of the following gives the correctly balanced half-equation for this half-reaction occurring under basic conditions?

A. $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$

B. $C_2H_5OH + 8OH^- \rightarrow CO_2 + 7H_2O + 8e^-$

C. $C_2H_5OH + 3H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$

D. $C_2H_5OH + 12OH^- \rightarrow 2CO_2 + 9H_2O + 12e^-$

Question 25

Which of the following statements is **incorrect** regarding primary galvanic cells?

A. A spontaneous redox reaction occurs, consuming energy.

B. The anode decreases in mass over the course of the reaction.

C. Negative ions travel across the salt bridge from the cathode to the anode.

D. The cathode is positively charged.

3F Faraday's Laws in galvanic and fuel cells

Question 26

The Avogadro constant is equal to

A. the number of particles in one mole of a substance.

B. the charge on one electron.

C. the number of moles in one particle of a substance.

D. the mass of one particle of any substance.

Question 27

The mass and volume of 1.0 mol of hydrogen gas, H_2, under standard laboratory conditions (SLC) are, respectively,

A. 1.0 g and 8.315 L

B. 1.0 g and 24.8 L

C. 2.0 g and 24.8 L

D. 2.0 g and 49.6 L

Question 28

The following is a half-equation occurring in some fuel cells.

$CH_3OH \rightarrow CO_2$

When this redox half-equation is correctly balanced, which of the following gives the stoichiometric ratio $n(CH_4) : n(e^-)$?

A. 1 : 1

B. 1 : 2

C. 1 : 4

D. 1 : 6

3G Fuel cell challenges and innovations

Question 29

A renewable feedstock is defined as

A. a material that is involved, but not consumed, in a reaction.

B. a raw material that can be replenished naturally in a short timeframe.

C. a resource consumed at a rate faster than it is produced.

D. a revolutionary cattle nutrition system.

Question 30

Fuel cells

A. convert chemical energy to electrical energy via the oxidation of a fuel.

B. convert electrical energy to chemical energy via the oxidation of a fuel.

C. convert chemical energy to electrical energy from a set amount of reactants.

D. convert electrical energy to chemical energy from a set amount of reactants.

4A Factors affecting the rate of reaction

Question 31

Which of the following formulas show the correct rearrangement of $pV = nRT$ to make the subject of the equation p?

A. $p = \frac{RT}{nV}$

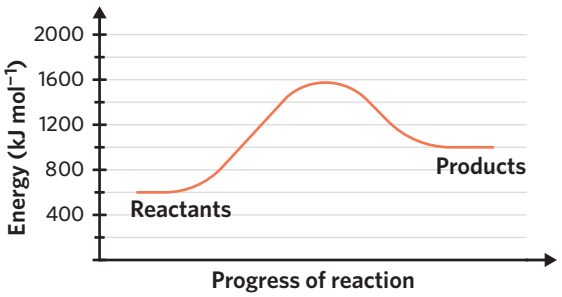
B. $p = \frac{nRT}{V}$

C. $p = \frac{VRT}{n}$

D. $p = \frac{V}{nRT}$

Question 32

The following diagram shows the energy profile for a reaction.



A catalyst reduces the activation energy by 250 kJ mol^{-1}. The value of the enthalpy change, in kJ mol^{-1}, of the catalysed reaction is

A. –600

B. 400

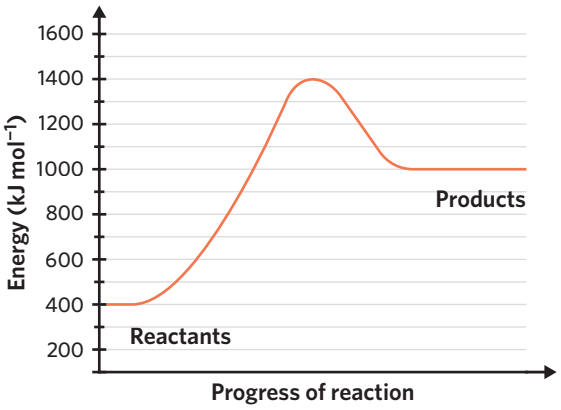
C. 750

D. 1000

4B Catalysts

Question 33

Consider the energy profile diagram below.



What is the activation energy of the forward reaction represented by this diagram?

A. 600 kJ mol^{-1}

B. 800 kJ mol^{-1}

C. 1000 kJ mol^{-1}

D. 1400 kJ mol^{-1}

Question 34

Which of the following statements is true of collision theory?

A. Whenever two particles collide, a reaction will occur.

B. Collisions occur only at higher temperatures.

C. Increasing the pressure of a reaction system will increase the proportion of successful collisions.

D. Decreasing the volume of a reaction system will increase the frequency of collisions.

5A Equilibrium reactions

Question 35

Which of the following is **not** a component of a combustion reaction?

A. Fuel

B. Heat

C. Oxygen

D. Nitrogen

Question 36

Consider the equation for the complete combustion of propane.

$C_3H_8 + 2O_2 \rightarrow 3CO_2 + 4H_2O$

If 6.5 mol of C_3H_8 combusts completely, how many moles of carbon dioxide will be produced?

A. 3 mol

B. 6.5 mol

C. 13 mol

D. 19.5 mol

Question 37

What is the effect of decreasing the temperature on the rate of a chemical reaction?

A. It increases the rate of the reaction.

B. It decreases the rate of the reaction.

C. It makes the reaction more exothermic.

D. It has no effect on the rate of the reaction.

5B Calculating equilibrium constants

Question 38

Which of the following statements is true regarding the energy changes in an exothermic reaction?

A. The products have more energy than the reactants.

B. The reaction absorbs energy from the surroundings.

C. The ΔH value is positive.

D. The energy released is in the form of heat.

Question 39

If the equilibrium constant for a reaction is 0.001, which of the following statements is true?

A. The reaction favours the products.

B. The reaction favours the reactants.

C. The reaction is close to equilibrium.

D. The reaction does not reach equilibrium.

5C Changes to equilibrium

Question 40

Which of the following is closest to the [NaOH] in a 3.7 L solution containing 400 g of NaOH?

A. 0.00925 M

B. 0.370 M

C. 2.70 M

D. 108 M

Question 41

Which of the following changes will result in an increased rate of reaction?

A. Decreasing the pressure of the reaction vessel

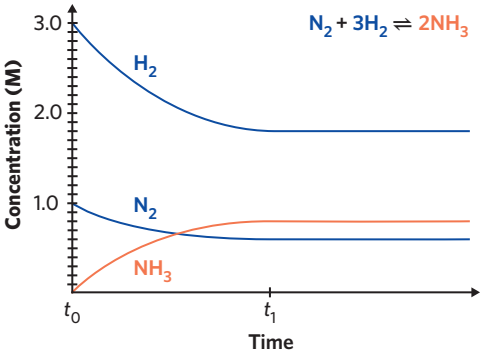
B. Increasing the volume of the reaction vessel

C. Using a powdered reactant instead of chips

D. Decreasing the temperature of the reaction

Question 42

Consider the concentration-time graph shown.



Which of the following correctly gives the $[N_2]$ at time t_0 and $[NH_3]$ at time t_1?

	$[N_2]$ at t_0	$[NH_3]$ at t_1
A.	1.0 M	0 M
B.	1.0 M	0.8 M
C.	3.0 M	0.6 M
D.	3.0 M	0.8 M

5D Compromise conditions

Question 43

Which of the following best describes how a catalyst speeds up a reaction?

A. A catalyst speeds up the formation of products by providing a reaction pathway with a lower activation energy.

B. A catalyst speeds up the formation of products and reactants by providing a reaction pathway with a higher activation energy.

C. A catalyst provides a reaction pathway with a lower activation energy, enabling a greater proportion of reactant particles to collide successfully.

D. A catalyst provides a reaction pathway with a higher activation energy, enabling a greater proportion of reactant particles to collide successfully.

Question 44

The following equation represents an aqueous reaction system.

$3X(aq) \rightleftharpoons Y(aq) + Z(aq) \quad \Delta H > 0$

When the system reaches equilibrium, 7.0 L of water is added. According to Le Chatelier's principle, the system would partially oppose this change by

A. favouring the formation of X.

B. favouring the formation of Y.

C. favouring the formation of Z.

D. None of the above

6A Electrolytic reactions

Question 45

Which of the following correctly identifies the oxidation states of all chemical species present in these unbalanced equations?

A. 0 +6 −2 +2 −2 +2
$Cu(s) + NO_3^-(aq) \rightarrow NO(g) + Cu^{2+}(aq)$

B. 0 +5 −2 +2 −2 +2
$Cu(s) + NO_3^-(aq) \rightarrow NO(g) + Cu^{2+}(aq)$

C. 0 +2 −1 +1 −1 +2
$Cu(s) + NO_3^-(aq) \rightarrow NO(g) + Cu^{2+}(aq)$

D. −2 +5 −2 +2 −2 +2
$Cu(s) + NO_3^-(aq) \rightarrow NO(g) + Cu^{2+}(aq)$

Question 46

Which of the following is a correct statement about the reactivity of solid zinc and cobalt?

A. Zn(s) is a stronger oxidising agent than Co(s).

B. Co(s) is a stronger oxidising agent than Zn(s).

C. Zn(s) is a stronger reducing agent than Co(s).

D. Co(s) is a stronger reducing agent than Zn(s).

Question 47

What is the reaction that occurs when a strip of zinc is placed in a 1.0 M Cu^{2+} solution?

A. $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

B. $Zn^{2+}(aq) + Cu(s) \rightarrow Zn(s) + Cu^{2+}(aq)$

C. $2Zn(s) + Cu^{2+}(aq) \rightarrow 2Zn^{2+}(aq) + Cu(s)$

D. No reaction occurs

6B Electrolytic cells

Question 48

Which of the following correctly gives the reactions that occur at the anode and cathode of primary galvanic cells and electrolytic cells?

	Primary Galvanic Cells		Electrolytic Cells	
	Anode	**Cathode**	**Anode**	**Cathode**
A.	Reduction	Oxidation	Oxidation	Reduction
B.	Oxidation	Reduction	Reduction	Oxidation
C.	Reduction	Oxidation	Reduction	Oxidation
D.	Oxidation	Reduction	Oxidation	Reduction

Question 49

Consider the following reactions that occur in a galvanic cell.

Reduction: $Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$ $E^0 = -0.13$ V

Oxidation: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ $E^0 = -0.76$ V

What is the maximum voltage predicted to be produced by this cell?

A. +0.63 V **B.** +0.89 V **C.** −0.89 V **D.** −0.63 V

Question 50

What is required to facilitate an electrolytic reaction?

A. Water

B. A suitable catalyst

C. Heat from the surroundings

D. Voltage input from a power source

6C Secondary cells

Question 51

Consider a spontaneous redox reaction that occurs according to the following overall redox equation.

$2Ag^+(aq) + Cu(s) \rightarrow 2Ag(s) + Cu^{2+}(aq)$

What is the oxidation half-reaction for this reaction?

A. $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

B. $Ag^+ + e^- \rightarrow Ag(s)$

C. $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$

D. $Ag(s) \rightarrow Ag^+(aq) + e^-$

Question 52

Which best describes the function of a primary galvanic cell?

	Energy conversion	Polarity of anode
A.	Electrical to chemical	Positive
B.	Chemical to electrical	Positive
C.	Electrical to chemical	Negative
D.	Chemical to electrical	Negative

Question 53

Consider a spontaneous redox reaction that occurs according to the following equation.

$Pb(s) + PbO_2(s) + H^+(aq) \rightarrow Pb^{2+}(aq) + H_2O(l)$

Given a sufficient voltage, what overall reaction is expected to occur when the products of this reaction are electrolysed?

A. $Pb(s) + PbO_2(s) + H^+(aq) \rightarrow Pb^{2+}(aq) + H_2O(l)$

B. $Pb^{2+}(aq) + H_2O(l) \rightarrow Pb(s) + PbO_2(s) + H^+(aq)$

C. $Pb^{2+}(aq) + 2H_2O(l) \rightarrow PbO_2(s) + 4H^+(aq) + 2e^-$

D. $Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$

Question 54

What is the voltage required to initiate the electrolysis of a 1.0 M $PbSO_4$ solution using inert electrodes, which involves the following half-reactions?

$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$ $E^0 = +1.23$ V

$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$ $E^0 = -0.13$ V

A. +1.36 V

B. −1.36 V

C. >+1.36 V

D. >−1.36 V

6D Designing cells to produce green hydrogen

Question 55

Renewable fuels

A. release less carbon dioxide than non-renewable fuels.

B. are replaced at least at the rate at which they are consumed.

C. directly contribute less to global warming than non-renewable fuels.

D. are all biofuels.

Question 56

Which one of the following fuels is the most sustainable?

A. Coal

B. Ethanol

C. Natural gas

D. Coal seam gas

Question 57

Which of the following is not required for photosynthesis to occur?

A. Energy

B. Carbon dioxide

C. Water

D. Glucose

6E Faraday's Laws in electrolytic cells

Question 58

In an electrochemical cell, 2.08 g of nickel is deposited at one electrode. The number of moles of electrons that passed through the cell is

A. 0.035 mol

B. 0.071 mol

C. 4.16 mol

D. 244 mol

Question 59

In an electrolytic cell with two solid electrodes,

A. mass is deposited at the anode, producing electricity.

B. mass is lost from the anode, producing electricity.

C. electricity must be input for mass to be deposited at the cathode.

D. electricity must be input for mass to be lost from the cathode.

7A Structures of organic compounds

Question 60

In a covalent bond, electrons are

A. shared between two atoms.

B. transferred from one atom to another.

C. delocalised.

D. not involved.

Question 61

Which of the following best describes electronegativity?

A. The tendency of an atom to gain protons

B. The tendency of an atom to lose protons

C. The tendency of an atom to gain electrons

D. The tendency of an atom to lose electrons

Question 62

What is **not** characteristic of a polar covalent bond?

A. Sufficient difference in electronegativity between two atoms

B. Uneven distribution of electrons over a covalent bond

C. Formation of partial charges on bonded atoms

D. Transfer of electrons between two atoms

7B Naming and properties of organic compounds

Question 63

Which of the following is **not** an intermolecular force?

A. Covalent bonding

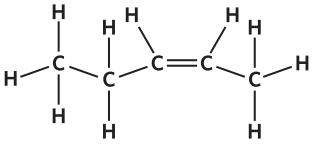
B. Hydrogen bonding

C. Dipole-dipole interactions

D. Dispersion forces

Question 64

What is the IUPAC name for the organic compound shown?



A. Pent-3-ene

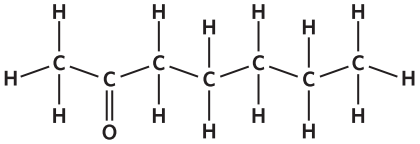
B. But-2-ene

C. But-3-ene

D. Pent-2-ene

Question 65

Consider the molecule shown



Which of the following gives the correct name for both the molecule's functional group and the type of molecule this structure represents?

	Functional group	Type of molecule
A.	Carbonyl	Aldehyde
B.	Carbonyl	Ketone
C.	Carboxyl	Aldehyde
D.	Carboxyl	Ketone

8A Types of organic reactions

Question 66

All biodiesel

A. has the same structural formula.

B. is made using methanol.

C. is made from triglycerides.

D. can be used in any car engine.

Question 67

Food contains energy that is stored in

A. chemical bonds.
B. the nucleus.
C. protons.
D. neutrons.

8B Sustainability of the production of chemicals

Question 68

Which one of the following fuels is the most sustainable?

A. Biodiesel
B. Uranium
C. Coal
D. Natural gas

Question 69

Which one of the following statements best defines a renewable energy resource?

A. An energy resource that will not be consumed within our lifetime
B. An energy resource that does not produce greenhouse gases when consumed
C. An energy resource derived from plants that are grown for the production of liquid biofuels
D. An energy resource that can be replaced by natural processes within a relatively short period of time

9A Testing for functional groups

Question 70

Which one of the following is a primary alcohol?

A. $CH_3CH(OH)CH_3$
B. $CH_3CH(OH)CH_2CH_3$
C. $CH_3CH_2CH_2OH$
D. $(CH_3)_3OH$

Question 71

Which of the following is the best definition of an unsaturated compound? A compound containing

A. carbon-carbon single bonds only.
B. single and carbon-carbon double bonds only.
C. carbon-carbon double and triple bonds only.
D. carbon-carbon double bonds only.

9B Analysis of consumer products

Question 72

A condenser is used to convert a

A. a liquid to a solid.
B. a solid to a liquid.
C. a gas to a liquid.
D. a liquid to a gas.

Question 73

Breaking the forces of attractions between particles is a relative measurement of

A. covalent bond strength.
B. ionic bond strength.
C. chemical change.
D. physical change.

Question 74

Crystal lattices are composed of

A. ions.
B. atoms.
C. elements.
D. compounds.

9C Volumetric analysis of redox reactions

Question 75

What is the mole a measure of?

A. Acidity
B. Basicity
C. Quantity
D. Quality

Question 76

In redox titrations a permanent change in colour is used to determine the _____ of a solution.

A. pH
B. end point
C. temperature
D. equivalence point

Question 77

An organic molecule that contains double or triple carbon-carbon bonds is

A. an alkane.
B. an alkene.
C. saturated.
D. unsaturated.

10A Mass spectrometry

Question 78

The relative atomic mass of chlorine is 35.5. What is the mass of 1 mol of chlorine atoms?

A. 17.5 g
B. 35.5 g
C. 70.5 g
D. 71.0 g

Question 79

How do isotopes of the same element differ from each other?

A. Number of protons
B. Number of electrons
C. Number of neutrons
D. Atomic number

10B Infrared spectroscopy

Question 80

Which of the following semi–structural formulas represents an organic compound containing a carbonyl functional group?

A. $CH_3CH_2CH_3$
B. $CH_3CH_2NH_2$
C. $CH_3OCH_2CH_3$
D. CH_3CH_2CHO

10C Low resolution carbon-13 nuclear magnetic resonance spectroscopy

Question 81

What is the name of the functional group present in ketones?

A. Hydroxyl group
B. Carbonyl group
C. Carboxyl group
D. Amine group

10D Low and high resolution proton nuclear magnetic resonance spectroscopy

Question 82

Which functional group is present in an alcohol?

A. Carbonyl group
B. Carboxyl group
C. Hydroxyl group
D. Alcohol group

Question 83

Which of the following compounds is correctly named using the IUPAC system?

A. 1-ethyl-3-methylpentane
B. 2-ethyl-4-methylpentane
C. 2-methyl-4-ethylhexane
D. 3-methyl-1-ethylpentane

Question 84

Chemical shift is expressed in

A. parts per million.
B. kilohertz.
C. hertz.
D. tesla.

10E Chromatography

Question 85

Which of the following solvents would be most effective for dissolving a non-polar solute?

A. Water
B. Methanol
C. 2-propanone
D. Hexane

Question 86

Which of the following statements about polar molecules is correct?

A. Polar molecules have an equal distribution of charge.
B. Polar molecules have an uneven distribution of charge.
C. Polar molecules have no net charge.
D. Polar molecules contain no covalent bonds.

10F Combining techniques

Question 87

A compound has the molecular formula $C_7H_{14}O_2$.
The compound could be

A. Heptanol
B. Octanoic acid
C. 2,3-dihydroxyoctane
D. Propyl butanoate

11A Extraction, purification and identifying medicinal molecules

Question 88

Polarity of molecules is caused by

A. bonds between atoms of similar electronegativity, combined with symmetry.

B. bonds between atoms of similar electronegativity, combined with asymmetry.

C. bonds between atoms of differing electronegativity, combined with symmetry.

D. bonds between atoms of differing electronegativity, combined with asymmetry.

Question 89

What does the symbol 'δ+' represent?

A. A full positive charge caused by a polar bond

B. A full positive charge on an ion

C. A partial positive charge caused by a polar bond

D. A partial positive charge on an ion

Question 90

Which of the following is **not** an appropriate representation of benzene?

A.  **B.**  **C.**  **D.** 

Question 91

Isomers

A. have the same molecular formula and structural formula.

B. have the same functional groups but a different number of carbon atoms.

C. have the same molecular formula but a different structural formula.

D. have the same empirical formula but a different molecular formula.

Question 92

Which of the following statements is **incorrect** regarding instrumental methods?

A. Mass spectroscopy can be used to determine the molecular mass of a compound.

B. HPLC can be used for qualitative and quantitative analysis of compounds in a mixture.

C. IR spectroscopy can be used to determine the number of carbon atoms in a compound.

D. NMR can be used to determine information about the functional groups in a compound.

11B Enzymes and medicines

Question 93

Which of the following is the best description of a structural feature common to all 2-amino acids (α-amino acids)?

A. Amino and carboxyl groups are located on the same carbon.

B. Amino and carboxyl groups are located on 2 different carbon atoms.

C. Carboxyl group is located on carbon number 2.

D. Amino group is located on carbon number 2.

Question 94

Amino acids are classified as amphiprotic because they can

A. either gain or lose a proton.

B. either gain or lose an electron.

C. lose an electron.

D. gain a proton.

Question 95

Which of the following cannot be used to determine the rate of a chemical reaction?

A. pH change

B. Mass loss

C. Gas evolution

D. Speed

12A Scientific research

Question 96

A student was aiming to investigate the relationship between pressure and the rate of H_2 gas production following the reaction between hydrochloric acid and solid magnesium. They make the following hypothesis: 'If the rate of reaction depends on pressure, then as pressure increases, H_2 gas will be produced at a faster rate.'

In this experiment, pressure

A. is the dependent variable.

B. is the independent variable.

C. is a controlled variable.

D. does not affect the results, so does not need to be kept constant.

12B Conducting an experiment

Question 97

Which of the following is an example of qualitative data?

A. The price of an ice cream

B. The temperature of an ice cream

C. The flavour of an ice cream

D. The mass of an ice cream

12C Interpreting data

Question 98

The _____ variable is manipulated by the experimenter, whilst the _____ variable is affected by the _____ variable.

A. independent, dependent, independent

B. dependent, independent, dependent

C. independent, dependent, dependent

D. dependent, independent, independent

Question 99

The mass of a sample is an example of

A. quasi data.

B. quandary data

C. quantitative data.

D. qualitative data.

Question 100

The eye colour of an individual is an example of

A. quasi data.

B. quandary data

C. quantitative data.

D. qualitative data.

12D Experimental factors affecting data

Question 101

Which of the following is a factor that can affect writing a conclusion?

A. The type of evidence used

B. How long the data took to analyse

C. What day the evidence was gathered

D. How many people were involved

12E Writing scientific material

Question 102

A hypothesis is

A. a prediction of how the independent variable will affect the dependent variable.

B. a prediction of what will happen in an experiment.

C. a prediction of how the dependent variable will affect the dependent variable.

D. the purpose of the experiment.

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Essential prior knowledge answers

1A	1. B	2. C	3. A			
1B	4. B					
1C	5. C	6. D				
1D	7. C	8. D	9. A			
2A	10. C	11. D	12. C			
2B	13. A					
2C	14. B	15. C				
3A	16. B	17. C				
3B	18. D	19. A				
3C	20. A	21. B				
3D	22. A	23. C				
3E	24. D	25. A				
3F	26. A	27. C	28. D			
3G	29. B	30. A				
4A	31. B	32. B				
4B	33. C	34. D				
5A	35. D	36. D	37. B			
5B	38. D	39. B				
5C	40. C	41. C	42. B			
5D	43. C	44. A				
6A	45. B	46. C	47. A			
6B	48. D	49. A	50. D			
6C	51. C	52. D	53. B	54. C		
6D	55. B	56. B	57. D			
6E	58. B	59. C				
7A	60. A	61. C	62. D			
7B	63. A	64. D	65. B			
8A	66. C	67. A				
8B	68. A	69. D				
9A	70. C	71. B				
9B	72. C	73. D	74. A			
9C	75. C	76. B	77. D			
10A	78. B	79. C				
10B	80. D					
10C	81. B					
10D	82. C	83. B	84. A			
10E	85. D	86. B				
10F	87. D					
11A	88. D	89. C	90. A	91. C	92. C	
11B	93. D	94. A	95. D			
12A	96. B					
12B	97. C					
12C	98. A	99. C	100. D			
12D	101. A					
12E	102. A					

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ANSWERS

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1A Fossil fuels

Progress questions

1. C. Fuels can combust in the presence of oxygen to produce heat energy.
2. B. Bacteria can break down large complex molecules into smaller simpler ones.
3. D. Coal seam gas is mainly composed of methane (> 90%) ethane, propane, and butane.
4. A. Fossil fuels take millions of years to form and cannot be replaced within a short period of time.
5. B. Petrol is a fossil fuel (non-renewable) that is found underground and is fractionally distilled from crude oil.
6. D. Coal contains many elements other than carbon – namely sulfur, which contributes to the formation of acid rain.

Deconstructed

7. C 8. D

9. [A non-renewable resource is one that cannot be replaced by natural processes within a relatively short period of time.[1]] [Natural gas, coal seam gas and methane hydrate are all non-renewable since their supplies, once used up, are not readily replenished.[2]] [Microbial decomposition (of plant material) will continue to produce methane within a short period of time as long as plant material is available, and so this is not a non-renewable energy source.[3]]

- ✓ ✗ I have defined a non-renewable resource.[1]
- ✓ ✗ I have identified the different sources of obtaining methane gas.[2]
- ✓ ✗ I have explained why methane gas obtained from natural, coal seam and methane hydrate gas are non-renewable, and why methane gas obtained from microbial decomposition in not non-renewable.[3]

Exam-style

10. C. Crude oil is a viscous mixture of hydrocarbons.

11. a. [Coal is a fossil fuel[1]] [because deposits are formed from organic matter decaying in sediments that are turned into coal over millions of years.[2]] [Natural gas is also a fossil fuel[3]] [as it is extracted from underground and was formed from the decomposition of plants and animals over millions of years.[4]]

- ✓ ✗ I have identified coal as a fossil fuel.[1]
- ✓ ✗ I have explained why coal is a fossil fuel.[2]
- ✓ ✗ I have identified natural gas as a fossil fuel.[3]
- ✓ ✗ I have explained why natural gas is a fossil fuel.[4]

b. [Fossil fuels have been formed from the remains of living organisms.[1]] [Therefore, ethanol produced from coal is a fossil fuel as coal has been formed from the remains of plants and animals over millions of years.[2]] [As a result, ethanol produced from this method can be considered as non-renewable as it cannot be replaced by natural processes within a relatively short period of time.[3]]

- ✓ ✗ I have explained the formation of fossil fuels.[1]
- ✓ ✗ I have linked the production of ethanol and the formation of fossil fuels.[2]
- ✓ ✗ I have linked my answer to the question.[3]

12. a. [Wood is a product of a recently living organism and grows relatively quickly,[1]] [whilst fossil fuels are formed from the decomposition of plants and/or marine creatures and/or animals over millions of years.[2]]

- ✓ ✗ I have identified how wood is produced.[1]
- ✓ ✗ I have identified how fossil fuels are produced.[2]

b. The amount of wood that would need to be grown would take land away from farming plants and animals or wood is not a sustainable energy source as it is burned more quickly than the trees can grow.

Key science skills

13. a. [Article 2 could be considered opinion, as it is written in a style that conveys the voice of an individual view or judgement formed about something, not necessarily based on fact or knowledge.[1]] [Article 1 represents information that has been gathered by a science agency and will therefore have quantitative evidence to back up the values.[2]]

- ✓ ✗ I have identified the article that is opinion.[1]
- ✓ ✗ I have justified why article 2 is not based on opinion.[2]

b. [Social.[1]] [This would mean many people would lose their jobs.[2]]

- ✓ ✗ I have identified a factor.[1]
- ✓ ✗ I have explained a reason why this factor could prevent the recommendations from being implemented.[2]

Alternative answer:

- Legal. Mining companies often have legally binding contracts with the government.

c. [Political.[1]] [The government earns a huge revenue from fossil fuels.[2]]

- ✓ ✗ I have identified a factor.[1]
- ✓ ✗ I have explained a reason why this factor could prevent the recommendations from being implemented.[2]

Alternative answer:

- Economic. The cost of coal would increase due to the lower supply and increased demand.

FROM LESSONS 12B & 12C

1B Biofuels

Progress questions

1. D. Biogas is a renewable mixture that contains mainly methane and carbon dioxide gas.

2. B. Biofuels create the same amount of carbon dioxide when combusted. Hydrogen is renewable but not a biofuel.

3. D. Renewable energy sources can be generated as quickly as they are used.

4. A. Net means the difference in the total amount created and consumed.

5. B. Biofuels can be sourced from plants and/or animals.

6. C. Yeast perishes when the % v/v of alcohol reaches a certain value – usually between 5 to 21% v/v.

Deconstructed

7. B **8.** A

9. a. [Growing.[1]][Seeds need to be bought, transported, and planted using machinery that would normally use non-renewables.[2]]

✓ ✗ I have identified a factor.[1]

✓ ✗ I have justified how this factor leads to the process not being carbon neutral.[2]

b. [Processing.[1]][Harvesting and processing the biomass use machinery that would normally use non-renewables.[2]]

✓ ✗ I have identified a factor.[1]

✓ ✗ I have justified how this factor leads to the process not being carbon neutral.[2]

Alternative answer:

- Transport. Delivering the biofuel uses machinery that would normally use non-renewables.

Exam-style

10. C. Methane is not a mixture, and triglycerides are not methyl esters.

11. C. Compost comes from biomass which can be regrown within a relatively short period of time.

12. a. [Yes.[1]][The sunflower crops used to produce the fuel can be replaced by natural processes within a relatively short period of time.[2]]

✓ ✗ I have identified biodiesel as a renewable energy source.[1]

✓ ✗ I have explained why biodiesel is renewable, with reference to the time taken to regrow the fuel.[2]

b. A large amount of water is required to cultivate the sunflower crops.

c. Transesterification reaction

d. Glycerol or propan-1,2,3-triol

13. a. X is (bio)ethanol and Y is carbon dioxide.

b. Bioethanol is considered a renewable fuel because it is derived from crops that can be replaced by natural processes within a relatively short period of time.

c. Carbon dioxide is a greenhouse gas, so it contributes to the enhanced greenhouse effect.

d. [Yes.[1]][Potatoes can be grown and cultivated in a relatively short period of time.[2]]

✓ ✗ I have identified bioethanol from potatoes as renewable.[1]

✓ ✗ I have explained why the origin of this bioethanol is regarded as renewable.[2]

Key science skills

14. a. [For: CO_2 is absorbed/used by the crops/plants (used to produce the bioethanol).[1]][Against: use of petrol (or other fuels) to produce bioethanol (resulting in CO_2 emissions)" – a large amount of energy is required to produce bioethanol fuel from sugarcane or other crops, as energy is needed for sowing, fertilising, harvesting, transporting and processing crops.[2]]

✓ ✗ I have discussed one valid point for the carbon neutrality of bioethanol.[1]

✓ ✗ I have discussed one valid point against the carbon neutrality of bioethanol.[2]

Alternative answers:

For:

- Bioethanol is more carbon neutral as it produces less new CO_2 than other fuels.

Against:

- Clearing land for crops by burning trees releases CO_2 and destroys habitats.
- There is less photosynthesis when land is cleared.
- Burning biomass directly emits more carbon dioxide than fossil fuels for the same amount of generated energy.

b. [For: plants can be produced/grown iat a rate that is greater or equal to the rate of consumption.[1]][Against: uses crops/land that could be used for food/food production.[2]]

✓ ✗ I have discussed one valid point for the sustainability of bioethanol.[1]

✓ ✗ I have discussed one valid point against the sustainability of bioethanol.[2]

Alternative answers:

For:

- Can be made from waste biomass
- Releases fewer toxic chemicals if spilled or released to the environment/many by-products are biodegradable
- Bioethanol produces less soot (particulate matter)/carbon monoxide/unburned hydrocarbons/sulfur dioxide.
- Crops (that produce oil) can be grown in many places.
- Can use second-generation technologies to convert material such as crop residues into bioenergy and avoid competition for land

Against:

- Some regions are not suitable for oil producing crops.
- The excess use of fertilisers can result in soil erosion and land pollution.
- Nitrous oxide released from fertilisers could have a greater (300 times more) global warming effect than carbon dioxide.
- The use of water to produce more crops can put pressure on local water resources.

c. [For: produces less toxic pollutants and greenhouse gases than petrol.[1]][Against: bioethanol fuel is more expensive than petrol fuel.[2]]

✓ ✗ I have discussed one valid point for the use of bioethanol as a fuel for transport.[1]

✓ ✗ I have discussed one valid point against the use of bioethanol as a fuel for transport.[2]

Alternative answers:

For:

- Reduces dependence on foreign oil reserves as it is domestically produced
- Can be used in any petrol engine with little or no modification to the engine or the fuel system

FROM LESSON 12E

Questions from multiple lessons

15. A. All the other options take millions of years to be replenished.
FROM LESSON 1A

16. C. Since coal, crude oil and uranium are non-renewable, the only viable option is option C – ethanol, methane and (bio)diesel can all be produced from renewable sources.
FROM LESSON 1A

17. [Biogas is considered renewable because its production-and-use cycle is continuous so that it is constantly replenished,[1]][whereas coal seam gas is used at a faster rate than it can be replenished, making it non-renewable.[2]]

✓ ✗ I have recalled the definitions of renewable and non-renewable.[1]

✓ ✗ I have explained which is renewable and non-renewable using the definitions.[2]

FROM LESSON 1A

18. Option A: Incorrect. A biofuel is a fuel produced from biomass that was alive in the recent past. Fossil fuels such as crude oil are produced by very slow geological processes.

Option B: Incorrect. Biofuels can also have significant environmental impact, e.g. use of land needed for food production to produce biofuel. Methane processed from biomass has the same environmental impact in that it is a greenhouse gas and produces CO_2 on combustion.

Option C: Correct. Ethene (CH_2CH_2), used to produce ethanol (by reaction with steam in the presence of an acid catalyst), is obtained from crude oil.

Option D: Incorrect. Hydrogen can also be obtained from coal – a fossil fuel. This hydrogen also does not produce CO_2 on combustion.

FROM LESSON 1A

1C Fuel for the body

Progress questions

1. D. Fats and oils provide 37 kJ of energy per gram, proteins provide 17 kJ of energy per gram, and carbohydrates provide 16 kJ of energy per gram.

2. B. Neither of these reactions can occur without water: the reactant glucose must be aqueous (in water), and water is a reactant in photosynthesis.

Deconstructed

3. B **4.** C **5.** A

6. C. Light is captured and utilised during photosynthesis to produce organic molecules (glucose) which are then oxidised to produce energy via cellular respiration.

Exam-style

7. D. As foods are a complex mixture of compounds their energy content is best measured according to their mass in grams.

8. D. Glucose is produced during photosynthesis.

9. B. Producing organic compounds using carbon dioxide, light, and water is a photosynthetic process.

10. a. (Cellular) respiration

b. [Similarity: both sugars contain the same non-metal elements carbon, hydrogen, and oxygen.[1]][Difference: sucrose (342.3 g mol^{-1}) has a greater molar mass than glucose (180.16 g mol^{-1}) – note that a sucrose molecule is made up of a glucose and a fructose molecule bonded together.[2]]

✓ ✗ I have explained a similarity.[1]

✓ ✗ I have explained a difference.[2]

c. $C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l)$

Key science skills

11. a. [Plants are able to produce their own food through a process called photosynthesis, which uses sunlight, water, and carbon dioxide to create glucose (a type of sugar) and oxygen.[1]] [Animals cannot produce their own food.[2]] [This makes plants independent of other organisms for their nutritional needs, whereas for animals they are dependent on plants for food.[3]]

- I have referenced an important chemical process that allows plants to survive on their own.[1]
- I have stated that animals cannot produce their own food .[2]
- I have linked my answer to the question for plants and animals.[3]

b. [Animals do not only depend on plants for energy from the process of cellular respiration, but also on other animals. For example, carnivores (animals that feed on other animals) rely on herbivores (animals that feed on plants) for their food source.[1]] [In addition, animals require other factors like shelter, water, and temperature regulation to survive, which they cannot produce on their own. Therefore, while plants are self-sufficient for their nutritional needs, animals are highly dependent on their environment and other organisms for survival.[2]] [Plants require the CO_2 produced by animal respiration and human activities to undergo photosynthesis, and, so they are not necessarily self-sufficient.[3]]

- I have referenced an important chemical process that results in animals not depending exclusively on plants for survival.[1]
- I have given examples of other factors that animals require for survival.[2]
- I have discussed how plants require carbon dioxide sources.[3]

FROM LESSON 12E

Questions from multiple lessons

12. a. [Reduced dependency on fossil fuels.[1]] [Bioethanol can be produced from renewable sources such as corn and sugarcane, reducing the reliance on fossil fuels and their associated environmental impacts.[2]] [Lower emission of some pollutants.[3]] [Photosynthesis takes in carbon dioxide.[4]]

- I have stated one advantage.[1]
- I have explained why it is an advantage.[2]
- I have stated a second advantage.[3]
- I have explained why it is an advantage.[4]

b. [Land use and food security concerns.[1]] [Large-scale production of bioethanol can lead to land-use change impacts, including deforestation, loss of arable land, soil erosion, and loss of biodiversity.[2]] [Not carbon neutral.[3]] [Although bioethanol is a renewable fuel source, the net greenhouse gas emissions from its production and use can still be significant when accounting for the full supply chain. These emissions can vary based on factors such as the energy source used in production and transportation.[4]]

- I have stated one disadvantage.[1]
- I have explained why it is a disadvantage.[2]
- I have stated a second disadvantage.[3]
- I have explained why it is a disadvantage.[4]

FROM LESSONS 1A & 1B

1D Enthalpy changes and combustion reactions

Progress questions

1. B. A reaction is endothermic if the energy absorbed to break chemical bonds in the reactants is greater than the energy released as bonds in the products are created.

2. D. Energy profile diagrams can be read backwards (right to left) to find information about the reverse reaction. The difference between the maximum energy reached by the system during the reaction and the initial energy of the reactants is the activation energy of a reaction.

3. C. This is a type of combustion reaction since it involves a fuel (methane gas) reacting with oxygen gas. Since a carbon-based product other than carbon dioxide is produced (carbon monoxide), this is an incomplete combustion reaction.

4. A. Combustion reactions are always exothermic, because the net enthalpy of the system decreases during these reactions. Enthalpy changes (ΔH) of exothermic reactions (including combustion reactions) are always written with a negative sign.

5. C. Answers B and D are examples of complete combustion as only carbon dioxide and water are produced. Answer A is unbalanced.

6. B. Thermochemical equations must include both a balanced chemical equation and a value of the enthalpy change (ΔH) during the reaction.

7. B. When a fuel undergoes complete combustion under SLC, the enthalpy change (ΔH) for the reaction in kJ mol^{-1} will be equal to the molar heat of combustion of the fuel (kJ mol^{-1}), regardless of any coefficients in front of the fuel. Combustion reactions are always exothermic and involve a net release of energy, so the sign will be negative.

8. C. The sign of the enthalpy change has reversed, so the new equation must represent the reverse reaction. The size of the enthalpy in kJ has tripled, so the coefficients in front of all reactants and products must also be tripled.

9. D. Complete combustion has occurred since carbon dioxide and water are the only products. Therefore, it is not possible to know which reactants are in excess.

10. A. This is an incomplete combustion reaction as carbon monoxide is produced. Incomplete combustion occurs when oxygen supply is limited.

11. B. Complete combustion occurs when oxygen is in excess. Carbon dioxide gas and water are the only products of complete combustion reactions.

Deconstructed

12. B **13.** C

14. a. $E_a = +30 \text{ kJ mol}^{-1} - 0 \text{ kJ mol}^{-1}$

$E_a = +30 \text{ kJ mol}^{-1}$ (1 MARK)

$\Delta H = +10 \text{ kJ mol}^{-1} - 0 \text{ kJ mol}^{-1}$

$\Delta H = +10 \text{ kJ mol}^{-1}$ (1 MARK)

b. A low activation energy of the reverse reaction would allow the reusable hand warmers to be easily 'reset' by being boiled for a short amount of time.

15. a. [Step 1,[1]][because the enthalpy of the products is higher than that of the reactant.[2]]

✓ ✗ I have identified the step involving an endothermic reaction.[1]

✓ ✗ I have justified my answer.[2]

b. $E_a = +250 \text{ kJ mol}^{-1} - 75 \text{ kJ mol}^{-1}$

$E_a = +175 \text{ kJ mol}^{-1}$

c. $\Delta H = 0 \text{ kJ mol}^{-1} - 75 \text{ kJ mol}^{-1}$

$\Delta H = -75 \text{ kJ mol}^{-1}$

Exam-style

16. D. If the energy absorbed by the system to break chemical bonds in the reactants is less than the energy released during the formation of chemical bonds, the system will undergo a net release of energy. Therefore, the reaction is exothermic.

17. A. The reaction of A and B to form X has a negative ΔH value, so there will be a 'step down' on the energy profile diagram. As X reacts to form C, there is a positive ΔH value, so there will be a 'step up' on the diagram. During the overall reaction (reaction of A and B to form C), there is a positive ΔH value, so there will be a 'step up' on the diagram between these stages of the reaction. This corresponds to answer A.

18. $C_{19}H_{32}O_2(l) + \frac{33}{2}O_2(g) \rightarrow 19CO(g) + 16H_2O(l/g)$ or $2C_{19}H_{32}O_2(l) + 33O_2(g) \rightarrow 38CO(g) + 32H_2O(l/g)$

19. The reverse reaction is shown with all coefficients doubled. Therefore, for a ΔH value in kJ, the molar heat of combustion from the VCE Data Book must be doubled and the sign must be reversed.

$\Delta H = 2 \text{ mol} \times (+2880 \text{ kJ mol}^{-1})$ (1 MARK)

$\Delta H = +5760 \text{ kJ}$ (1 MARK)

20. The molar heat of combustion according to the VCE Data Book is 726 kJ mol^{-1} for complete combustion reactions under SLC. For an enthalpy change (ΔH) in kJ, this value needs to be doubled as 2 moles of methanol are combusted. Since combustion reactions are exothermic, the sign will be negative.

$\Delta H = 2 \text{ mol} \times (-726 \text{ kJ mol}^{-1})$

$\Delta H = -1452 \text{ kJ}$

21. a. $C_4H_{10}(l/g) + \frac{13}{2}O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l/g)$

$\Delta H = -2880 \text{ kJ mol}^{-1}$

or $2C_4H_{10}(l/g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(l/g)$

$\Delta H = -5760 \text{ kJ}$

b. [The lack of carbon dioxide produced in this reaction would indicate that incomplete combustion has occurred to produce carbon based products other than carbon dioxide, such as carbon monoxide and carbon (soot), as well as water.[1]] [This indicates that there was a limited supply of oxygen present in the surrounding environment.[2]]

✓ ✗ I have identified the type of combustion reaction that occurred.[1]

✓ ✗ I have linked this fact to the limited supply of oxygen in the external environment.[2]

c. [The conversion of liquid water to water vapour is an endothermic reaction,[1]][as energy is absorbed by the water molecules in order to overcome the intermolecular forces that keep water molecules in a liquid state, rather than a gas.[2]]

✓ ✗ I have identified whether it is an endothermic or exothermic process.[1]

✓ ✗ I have justified my answer by referring to the process involved in state changes.[2]

Key science skills

22. a. [The black substance that coated the first crucible is soot. Its production indicates that incomplete combustion has occurred,[1]][and the closed air holes also suggest that oxygen supply was limited.[2]][When the air holes were opened, oxygen was in excess.[3]][Therefore, complete combustion occurred to produce only carbon dioxide gas and water, so no coating was observed.[4]]

✓ ✗ I have identified the type of reaction and its products.[1]

✓ ✗ I have explained why this reaction has occurred in terms of oxygen supply.[2]

✓ ✗ I have explained why this reaction has occurred in terms of oxygen supply.[3]

✓ ✗ I have identified the type of reaction and its products.[4]

b. i. [Even if complete combustion does not occur, more oxygen will be available to oxidise the fuel.[1]][This means that little to no carbon (soot) may be produced, with CO and CO_2 being the main products of this incomplete combustion reaction.[2]]

✓ ✗ I have identified the type of combustion reaction that is likely to occur with reference to availability of oxygen.[1]

✓ ✗ I have identified the likely products of this reaction.[2]

ii. [Anastasiya should consider that even though some more oxygen will be let in, it still may not be in excess, meaning incomplete combustion would occur. Therefore, a visible coating may still be observed.[1]][Since more oxygen is available to react, there may be less soot produced as CO and CO_2 will be more readily created.[2]]

✓ ✗ I have identified the type of combustion reaction that is likely to occur with reference to availability of oxygen.[1]

✓ ✗ I have identified the likely products of this reaction.[2]

c. i. Qualitative data

ii. The change in the mass of the crucibles before and after heating

FROM LESSONS 12B & 12C

Questions from multiple lessons

23. a. The amount of biodiesel in moles cannot be determined, as it is a mixture. Therefore, its enthalpy cannot be expressed in kJ mol^{-1}.

b. $\Delta H = -37 \text{ kJ g}^{-1} \times 200 \text{ g}$

$\Delta H = -7.4 \times 10^3 \text{ kJ}$

FROM LESSON 1B

24. a. $C_3H_8(g) + 3O_2(g) \rightarrow 2CO(g) + C(s) + 4H_2O(l/g)$

Alternative answers:

- $C_3H_8(g) + \frac{5}{2}O_2(g) \rightarrow CO(g) + 2C(s) + 4H_2O(l/g)$
- $2C_3H_8(g) + 5O_2(g) \rightarrow 2CO(g) + 4C(s) + 8H_2O(l/g)$

b. [No.[1]][Carbon that has been stored in deposits for millions of years is released into the atmosphere when the fuel is combusted, in this case in the form of carbon monoxide gas and solid carbon.[2]]

✓ ✗ I have stated whether this fuel is carbon neutral.[1]

✓ ✗ I have explained my answer with reference to the release of stored carbon into the atmosphere.[2]

FROM LESSON 1A

Chapter 1 review

Multiple choice

1. B. Since coal, natural gas (mainly methane), and coal seam gas (mainly methane) are non-renewable, the only viable option is B as (bio)ethanol can be produced from renewable sources.

2. D. Petrol is derived from fossil fuels and electricity can be generated from any fuel. Biogas contains carbon; therefore, it produces carbon dioxide when combusted.

3. C. Biofuels are from renewable sources such as plants; coal is a fossil fuel.

4. B. Biodiesels are made up of long hydrocarbon chains and contain two oxygen atoms as part of the ester bond.

5. D. Proteins are normally not broken down to be used as a source of energy.

6. A. Biodiesel is produced by adding methanol (in alkaline conditions) to triglycerides by a process known as transesterification.

7. C. The main reactants are water and carbon dioxide in the presence of sunlight.

8. C. Options A and C represent the products of incomplete combustion, which signifies that oxygen is the limiting reagent. Only C is balanced.

9. B. The reverse reaction is exothermic (negative sign) and the number of moles of ethanol is halved.

10. C. Equations consistent with each energy profile:

Option A: $2NO_2(g) \rightarrow 2NO(g) + O_2(g) \quad \Delta H = -14$ kJ (value incorrectly shown as an endothermic reaction in the question)

Option B: $CO_2(g) + NO(g) \rightarrow CO(g) + NO_2(g) \quad \Delta H = -226$ kJ (value for the forward reaction incorrectly shown as an exothermic reaction in the question)

Option C: $N_2O_4(g) \rightleftharpoons 2NO_2(g) \quad \Delta H = +57$ kJ or for the reverse reaction $2NO_2(g) \rightleftharpoons N_2O_4(g) \quad \Delta H = -57$ kJ

Option D: $N_2(g) + O_2(g) \rightleftharpoons 2NO(g) \quad \Delta H = -181$ kJ (value incorrectly shown as an endothermic reaction in the question)

Short answer

11. a. [$C_3H_8(g) + 5O_2(g)$[1]][$\rightarrow 3CO_2(g) + 4H_2O(l)$[2]]
[$\Delta H = -2220$ kJ mol^{-1} or kJ[3]]

✓ ✗ I have written the formulas for the reactants and balanced the equation including state symbols.[1]

✓ ✗ I have written the formulas for the products and balanced the equation including state symbols.[2]

✓ ✗ I have written the enthalpy change value using the VCE Data Book including units and symbols.[3]

b. [$C_3H_8(g) + 3\frac{1}{2}O_2(g)$[1]][$\rightarrow 3CO(g) + 4H_2O(l)$[2]]

✓ ✗ I have written the formulas for the reactants and balanced the equation including state symbols.[1]

✓ ✗ I have written the formulas for the products and balanced the equation including state symbols.[2]

Alternative answers:

- $C_3H_8(g) + 2O_2(g) \rightarrow 3C(s) + 4H_2O(l)$

c. Given that the overall enthalpy change comes from the amount of bonds broken and formed, it is predicted that the enthalpy change value would be less, as fewer bonds are both broken (endothermic) and formed (exothermic).

12. a. [For a fuel to be considered renewable it must be easily replenished by natural processes within a relatively short period of time.[1]][Ethanol sourced from coal is not easily replaced as fossilisation of organic matter occurs over millions of years, so is non-renewable. However, ethanol sourced from sweet potato crops can be replaced within a relatively short period of time, so is renewable.[2]]

✓ ✗ I have defined a renewable fuel source.[1]

✓ ✗ I have used my definition to describe why ethanol can be either renewable or non-renewable depending on its source.[2]

b. [$C_6H_{12}O_6(aq) \rightarrow 2C_2H_5OH(aq)$[1]][$+ 2CO_2(g)$[2]]

✓ ✗ I have written the formula and state symbol for glucose and ethanol.[1]

✓ ✗ I have balanced the equation.[2]

c. [The production of sweet potato crops would absorb carbon dioxide to offset the amount released when combusted,[1]] [whereas ethanol sourced from coal deposits would not.[2]]

✓ ✗ I have identified carbon offsetting as an advantage of farming sweet potatoes.[1]

✓ ✗ I have compared this to coal deposit sourcing.[2]

d. The clearing of land to produce sweet potato crops may damage animal habitats.

13. a. [A renewable fuel is easily replaced by natural processes within a relatively short period of time.[1]] [The petrol product is obtained from crude oil underground formed over millions of years, so it is not considered renewable.[2]]

✓ ✗ I have defined a renewable fuel.[1]

✓ ✗ I have used this definition to explain why petrol is not renewable.[2]

b. [Petrol is made up of a long non-polar hydrocarbon chain, with no functional groups.[1]] [Therefore, the only intermolecular forces between petrol molecules are dispersion forces.[2]]

✓ ✗ I have identified the structure of petrol.[1]

✓ ✗ I have used the structure to identify the intermolecular force that is present.[2]

c. [Biodiesel contains a polar ester linkage, which allows it to form permanent dipole-dipole interactions.[1]] [These dipole-dipole forces are significantly stronger than the dispersion forces present in petrol.[2]] [As a result, more energy will be required to disrupt the intermolecular forces, leading to a higher boiling point for the mixture.[3]]

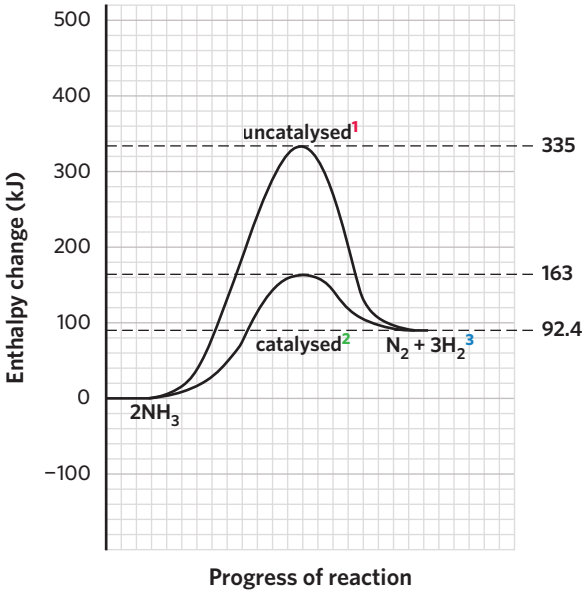
✓ ✗ I have identified the primary intermolecular force present in biodiesel.[1]

✓ ✗ I have related the strength of these forces to those of petrol.[2]

✓ ✗ I have explained how this difference will affect the mixture's boiling point.[3]

d. Combustion of petrol releases the greenhouse gas carbon dioxide into the atmosphere, which contributes to the enhanced greenhouse effect.

14.



✓ ✗ I have drawn the correct shape for the uncatalysed profile in the correct location.[1]

✓ ✗ I have drawn the correct shape of the catalysed profile in the correct location.[2]

✓ ✗ I have correctly represented the enthalpy of the products.[3]

15. a. [A sustainable resource can be produced at a rate that is greater than or equal to the rate of consumption.[1]] [Natural gas is obtained from coal deposits which are formed over millions of years and are rapidly depleted, meaning it is not a sustainable resource.[2]]

✓ ✗ I have defined a sustainable resource.[1]

✓ ✗ I have used this definition to explain why electricity sourced from natural gas is not sustainable.[2]

b. mass (g) of CO_2 per 75 km

$$= \frac{m(CO_2)}{L} \times \frac{L}{100\text{ km}} \times \frac{75\text{ km}}{100}$$

Car 1: $1750 \times 21.3 \times 0.75 = 27\,956$ g

Car 2: $2479 \times 17.6 \times 0.75 = 32\,723$ g

Car 3: $2453 \times 17.3 \times 0.75 = 31\,828$ g

Car 4: $2871 \times 11.4 \times 0.75 = 24\,547$ g (1 MARK)

Therefore, car 4 has the lowest amount of carbon dioxide released per 75 km. (1 MARK)

c. [Bioethanol is primarily produced from the fermentation of glucose sourced from crops, which absorb carbon dioxide during growth, and so when bioethanol is combusted, the net release of carbon dioxide into the atmosphere is minimal.[1]] [Petrol is sourced from ancient remains of both plants and animals and so has a smaller amount of carbon offsetting, leading to a significantly higher net amount of carbon dioxide released into the atmosphere compared to bioethanol.[2]]

✓ ✗ I have used the origin of bioethanol to explain its net carbon dioxide impact.[1]

✓ ✗ I have compared the net environmental impact of bioethanol and petrol.[2]

Key science skills

16. a. [Independent variable: type of fuel.[1]] [Dependent variable: boiling point.[2]]

✓ ✗ I have identified the independent variable.[1]

✓ ✗ I have identified the dependent variable.[2]

b. [Whilst the hydrogen bonds of ethanol are significantly stronger than petrol's dispersion forces,[1]] [petrol molecules have hydrocarbon chains that are long enough to generate an overall intermolecular dispersion force that is actually stronger than these hydrogen bonds.[2]]

✓ ✗ I have made a reference to the different intermolecular forces present in ethanol and petrol.[1]

✓ ✗ I have suggested a reason for the differences in each fuel's boiling point.[2]

c. [To improve the precision of the results, the engineer could repeat the experiment multiple times under the same experimental conditions and take the average of these results.[1]] [This could be done in order to reduce the effects of any random errors.[2]]

✓ ✗ I have identified how the engineer could improve the precision of their results.[1]

✓ ✗ I have described why this method will improve the precision of the results.[2]

FROM LESSONS 12A & 12D

17. [Similarities: Both processes involve the conversion of energy from one form to another.[1]] [Both processes require water.[2]] [Differences: Photosynthesis involves the consumption of carbon dioxide and release of oxygen, whereas cellular respiration involves the consumption of oxygen and release of carbon dioxide.[3]] [Photosynthesis occurs in the chloroplasts of plant cells, whilst cellular respiration occurs in the mitochondria of cells.[4]]

✓ ✗ I have identified a first similarity between the processes.[1]

✓ ✗ I have identified a second similarity between the processes.[2]

✓ ✗ I have identified a first difference between the processes.[3]

✓ ✗ I have identified a second difference between the processes.[4]

Alternative answers:

Similarities:

- Both can occur in plant cells.
- Both of these processes cycle the same molecules: carbon dioxide, oxygen, glucose, and water.

Differences:

- Photosynthesis converts light energy into chemical energy, whilst cellular respiration converts chemical energy into ATP.
- Photosynthesis involves the use of chlorophyll and other pigments to absorb light energy, whilst cellular respiration does not require pigments.
- Glucose is created in photosynthesis but broken down in cellular respiration.
- Cellular respiration is exothermic, whereas photosynthesis is endothermic.
- The simplified overall equations are the reverse of each other.

FROM LESSON 12E

2A Calculating energy changes from combustion

Progress questions

1. A. $n(H_2O) = \frac{m}{M}$

$n(H_2O) = \frac{18\text{ g}}{18.0\text{ g mol}^{-1}}$

$n(H_2O) = 1.0\text{ mol}$

$n(CH_4) : n(H_2O)$

1 : 2

$n(CH_4) = \frac{1}{2} \times 1.0\text{ mol}$

$n(CH_4) = 0.50\text{ mol}$

$m(CH_4) = n \times M$

$m(CH_4) = 0.50\text{ mol} \times 16.0\text{ g mol}^{-1}$

$m(CH_4) = 8.0\text{ g}$

2. A. Although CO is harmful to inhale, it does not contribute to the enhanced greenhouse effect.

3. C. $n(CO_2) = \frac{10\text{ L}}{24.8\text{ L mol}^{-1}}$

$n(CO_2) = 0.403\text{ mol}$

$m(CO_2) = 0.403\text{ mol} \times (12.0\text{ g mol}^{-1} + 2 \times 16.0\text{ g mol}^{-1})$

$m(CO_2) = 18\text{ g}$

4. D. At constant temperature and pressure, we can use the formula

$V(\text{unknown}) = \frac{\text{coefficient of the unknown species}}{\text{coefficient of the known species}} \times V(\text{known})$

$V(CO_2) = \frac{4}{1} \times V(C_4H_{10})$

$V(CO_2) = \frac{4}{1} \times 13\text{ L}$

$V(CO_2) = 52\text{ L}$

5. A. $\Delta H(C_2H_5OH) = -29.6\text{ kJ g}^{-1}$

Energy $= 43.0\text{ g} \times 29.6\text{ kJ g}^{-1}$

Energy $= 1.27 \times 10^3\text{ kJ}$

6. B. $n(H_2) = \frac{50.0\text{ L}}{24.8\text{ L mol}^{-1}}$

$n(H_2) = 2.0161\text{ mol}$

$\Delta H(H_2) = -282\text{ kJ mol}^{-1}$

Energy $= 2.0161\text{ mol} \times 282\text{ kJ mol}^{-1}$

Energy $= 5.69 \times 10^2\text{ kJ}$

Deconstructed

7. D **8.** C

9. Energy released per 1.00 g of

$\text{E10} = \left(\frac{0.90\text{ g octane}}{1.00\text{ g E10}} \times 47.9\text{ kJ g}^{-1}\right) + \left(\frac{0.10\text{ g ethanol}}{1.00\text{ g E10}} \times 29.6\text{ kJ g}^{-1}\right)$

Energy released per 1.00 g of E10 $= 43.11\text{ kJ g}^{-1} + 2.96\text{ kJ g}^{-1}$

Energy released per 1.00 g of E10 $= 46.07\text{ kJ g}^{-1}$ (1 MARK)

Mass of E10 fuel in a full tank $= \frac{2.396 \times 10^6\text{ kJ}}{46.07\text{ kJ g}^{-1}}$

Mass of E10 fuel in a full tank $= 5.20 \times 10^4\text{ g}$ (1 MARK)

Exam-style

10. A. From 2 moles of TNT, n(gases produced) $= 20$ mol

From 1 mole of TNT, n(gases produced) $= 10$ mol

From 1 mole of TNT, V(gases produced) $= 10\text{ mol} \times 24.8\text{ L mol}^{-1}$

From 1 mole of TNT, V(gases produced) $= 248\text{ L}$

11. B. Energy from 100 g of butane $= 100\text{ g} \times 49.7\text{ kJ g}^{-1}$

Energy from 100 g of butane $= 4970\text{ kJ}$

Energy from 200 g of octane $= 200\text{ g} \times 47.9\text{ kJ g}^{-1}$

Energy from 200 g of octane $= 9580\text{ kJ}$

Total energy released $= 4970\text{ kJ} + 9580\text{ kJ}$

Total energy released $= 14\,550\text{ kJ}$

Total energy released $= 146 \times 10^2\text{ kJ}$

12. a. i. 1 mol of octane produces 5460 kJ of energy.

$1.000\text{ MJ} = 1.000 \times 10^3\text{ kJ}$

$n(C_8H_{18}) = \frac{1.000 \times 10^3\text{ kJ}}{5460\text{ kJ mol}^{-1}}$

$n(C_8H_{18}) = 0.18315\text{ mol}$

ii. 1 mol of ethanol produces 1360 kJ of energy.

$n(C_2H_5OH) = \frac{1.000 \times 10^3\text{ kJ}}{1360\text{ kJ mol}^{-1}}$

$n(C_2H_5OH) = 0.73529\text{ mol}$

b. i. From the combustion reaction equation of octane:

$n(CO_2) = \frac{8}{1} \times n(C_8H_{18})$

$n(CO_2) = \frac{8}{1} \times 0.18315\text{ mol}$

$n(CO_2) = 1.4652\text{ mol}$

ii. From the combustion reaction equation of ethanol:

$n(CO_2) = \frac{2}{1} \times n(C_2H_5OH)$

$n(CO_2) = \frac{2}{1} \times 0.73529\text{ mol}$

$n(CO_2) = 1.4706\text{ mol}$

c. i. For the combustion of octane at SLC:

$V(CO_2) = V_m \times n(CO_2)$

$V(CO_2) = 24.8\text{ L mol}^{-1} \times 1.4652\text{ mol}$

$V(CO_2) = 36.3\text{ L}$

ii. For the combustion of ethanol at SLC:

$V(CO_2) = V_m \times n(CO_2)$

$V(CO_2) = 24.8\text{ L mol}^{-1} \times 1.4706\text{ mol}$

$V(CO_2) = 36.5\text{ L}$

d. At SLC, octane contributes slightly less to the enhanced greenhouse effect, though the difference is essentially negligible.

13. a. $n(C_3H_8) = \frac{2.3\text{ g}}{44.0\text{ g mol}^{-1}}$

$n(C_3H_8) = 0.05227\text{ mol}$ (1 MARK)

From equation, $n(CO_2) = \frac{3}{1} \times n(C_3H_8)$

$n(CO_2) = \frac{3}{1} \times 0.05227\text{ mol}$

$n(CO_2) = 0.1568\text{ mol}$ (1 MARK)

$V(CO_2) = V_m \times n(CO_2)$

$V(CO_2) = 24.8\text{ L mol}^{-1} \times 0.1568\text{ mol}$

$V(CO_2) = 3.9\text{ L}$ (2 sig. figs) (1 MARK)

b. [Burning propane in its liquid form would produce less energy than if it were burnt in its gaseous form.[1]][This is because some energy released in this reaction would be absorbed by remaining liquid propane, allowing the phase change from liquid to gas to occur. This phase change requires a certain amount of energy to first be absorbed by the system in order to disrupt the intermolecular forces, decreasing the net energy released.[2]]

I have determined that the combustion of the liquid would produce less energy.[1]

I have justified my answer with reference to the enthalpy of the state change from liquid to gas.[2]

14. a. $\text{density of petrol} = \frac{\text{mass of fuel used per 100 km}}{\text{fuel economy}}$

$\text{density of petrol} = \frac{14.0\text{ kg / 100 km}}{18.9\text{ L /100 km}}$

$\text{density of petrol} = 0.74074\text{ kg L}^{-1}$

$\text{density of petrol} = 0.741\text{ kg L}^{-1}$ (3 sig. figs)

b. i. $m(\text{diesel})\text{ per 100 km} = \text{density} \times \text{fuel economy}$

$m(\text{diesel})\text{ per 100 km} = 0.838\text{ kg L}^{-1} \times 12.0\text{ L per 100 km}$

$m(\text{diesel})\text{ per 100 km} = 10.056\text{ kg per 100 km}$

$m(\text{diesel})\text{ per 100 km} = 10.1\text{ kg per 100 km}$ (3 sig. figs)

ii. $m(\text{LPG})\text{ per 100 km} = \text{density} \times \text{fuel economy}$

$m(\text{LPG})\text{ per 100 km} = 0.493\text{ kg L}^{-1} \times 19.7\text{ L per 100 km}$

$m(\text{LPG})\text{ per 100 km} = 9.7121\text{ kg per 100 km}$

$m(\text{LPG})\text{ per 100 km} = 9.71\text{ kg per 100 km}$ (3 sig. figs)

c. i. $n(\text{LPG})\text{ per 100 km} = \frac{m\text{ per 100 km}}{M}$

$n(\text{LPG})\text{ per 100 km} = \frac{9.7121 \times 10^3\text{ g per 100 km}}{44.0\text{ g mol}^{-1}}$

$n(\text{LPG})\text{ per 100 km} = 220.73\text{ mol per 100 km}$ (1 MARK)

From equation, $n(CO_2)\text{ per 100 km} = \frac{3}{1} \times n(\text{LPG})\text{ per 100 km}$

$n(CO_2)\text{ per 100 km} = \frac{3}{1} \times 220.73\text{ mol per 100 km}$

$n(CO_2)\text{ per 100 km} = 662.19\text{ mol per 100 km}$ (1 MARK)

$m(CO_2)\text{ per 100 km} = M(CO_2) \times n(CO_2)\text{ per 100 km}$

$m(CO_2)\text{ per 100 km} = 44.0\text{ g mol}^{-1} \times 662.19\text{ mol per 100 km}$

$m(CO_2)\text{ per 100 km} = 2.914 \times 10^4\text{ g per 100 km}$

$m(CO_2)\text{ per 100 km} = 29.1\text{ kg per 100 km}$ (3 sig. figs) (1 MARK)

ii. $n(\text{petrol})\text{ per 100 km} = \frac{m\text{ per 100 km}}{M}$

$n(\text{petrol})\text{ per 100 km} = \frac{1.40 \times 10^4\text{ g per 100 km}}{114.0\text{ g mol}^{-1}}$

$n(\text{petrol})\text{ per 100 km} = 122.81\text{ mol per 100 km}$ (1 MARK)

From equation, $n(CO_2)\text{ per 100 km} = \frac{8}{1} \times n(\text{petrol})\text{ per 100 km}$

$n(CO_2)\text{ per 100 km} = \frac{8}{1} \times 122.81\text{ mol per 100 km}$

$n(CO_2)\text{ per 100 km} = 982.46\text{ mol per 100 km}$ (1 MARK)

$m(CO_2)\text{ per 100 km} = M(CO_2) \times n(CO_2)\text{ per 100 km}$

$m(CO_2)\text{ per 100 km} = 44.0\text{ g mol}^{-1} \times 982.46\text{ mol per 100 km}$

$m(CO_2)\text{ per 100 km} = 4.3228 \times 10^4\text{ g per 100 km}$

$m(CO_2)\text{ per 100 km} = 43.2\text{ kg per 100 km}$ (3 sig. figs) (1 MARK)

d. LPG

Key science skills

15. a. This trial is not valid as what it actually measures (the heat of combustion of a methanol/octane fuel) is different from what it claims to measure (the heat of combustion of an ethanol/octane fuel).

b. [Methanol's heat of combustion (22.7 kJ g^{-1}) is lower than that of ethanol (29.6 kJ g^{-1}),[1]][and so the combustion of approximately 2.0 g of methanol (20% of 10.0 g) would release less energy than the combustion of approximately 2.0 g of ethanol.[2]][This means that the 'Energy produced' value for Trial #2 was lower than it would have otherwise been, causing a decrease in the final calculated value for the fuel mixture's heat of combustion.[3]]

I have compared the heats of combustion of methanol and ethanol.[1]

I have explained that the mixture containing methanol released less energy than if ethanol were used.[2]

I have explained that this caused a decrease in the mixture's calculated heat of combustion.[3]

c. [Since this fuel mixture's percentage composition varies across batches, it is neither logical nor useful to calculate its molar heat of combustion, as the mixture's exact molar mass cannot be known.[1]][Accordingly, calculating a 'molar heat of combustion' for this fuel is not repeatable, as the value determined could differ significantly depending on the batch.[2]]

I have explained that it is not sensible to calculate molar heat of combustion values for mixtures.[1]

I have explained that this experiment would not be repeatable.[2]

FROM LESSON 12D

Questions from multiple lessons

16. a. $M(C_8H_{18}) = 114.0\ g\ mol^{-1}$

$M(C_2H_5OH) = 46.0\ g\ mol^{-1}$

$1.00\ mol\ C_8H_{18} + 1.00\ mol\ C_2H_5OH$

$= (1\ mol \times 114.0\ g\ mol^{-1}) + (1\ mol \times 46.0\ g\ mol^{-1})$

$1.00\ mol\ C_8H_{18} + 1.00\ mol\ C_2H_5OH = 160\ g$ of fuel mixture (1 MARK)

$80\ g$ of fuel mixture $= 0.50\ mol\ C_8H_{18} + 0.50\ mol\ C_2H_5OH$

$\Delta H(C_8H_{18}) = -5460\ kJ\ mol^{-1}$

$\Delta H(C_2H_5OH) = -1360\ kJ\ mol^{-1}$

Energy released $= (0.50\ mol \times 5460\ kJ\ mol^{-1}) + (0.50\ mol \times 1360\ kJ\ mol^{-1})$ (1 MARK)

Energy released $= 2730\ kJ + 680\ kJ$

Energy released $= 34 \times 10^2\ kJ$ (2 sig. figs) (1 MARK)

b. [The vast majority of ethanol is sourced from plants (as bioethanol), whereas petrol is sourced from crude oil (a fossil fuel).[1]][Therefore, ethanol is renewable and much more likely to be a sustainable resource than petrol, which takes millions of years to replenish.[2]]

I have referred to the respective sources of ethanol and petrol.[1]

I have identified sustainability as an advantage of ethanol over petrol.[2]

Alternative answer:

- The growing of crops to produce ethanol absorbs CO_2, which offsets CO_2 produced in the combustion of ethanol and results in less net CO_2 being released from using ethanol compared with octane.

FROM LESSON 1B

17. a. i. $[H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)^{1}]$ $[\Delta H = -282\ kJ^{2}]$ (mol^{-1})

I have written a balanced combustion equation.[1]

I have written an appropriate ΔH value for the equation.[2]

Alternative answer:

- $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$ $\Delta H = -564\ kJ$

ii. $[CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)^{1}]$
$[\Delta H = -890\ kJ\ (mol^{-1})^{2}]$

I have written a balanced combustion equation.[1]

I have written an appropriate ΔH value for the equation.[2]

b. $V(CH_4) = 2.0\ L$

$n(CH_4) = \dfrac{2.0\ L}{24.8\ L\ mol^{-1}}$

$n(CH_4) = 0.0806\ mol$ (1 MARK)

$\Delta H(CH_4) = 890\ kJ\ mol^{-1}$

Energy released by $CH_4 = 0.0806\ mol \times 890\ kJ\ mol^{-1}$

Energy released by $CH_4 = 71.77\ kJ$ (1 MARK)

$n(H_2) = \dfrac{\text{energy released}}{\text{molar heat of combustion of } H_2}$

$n(H_2) = \dfrac{71.77\ kJ}{282\ kJ\ mol^{-1}}$

$n(H_2) = 0.2545\ mol$ (1 MARK)

$V(H_2) = 0.2545\ mol \times 24.8\ L\ mol^{-1}$

$V(H_2) = 6.3\ L$ (2 sig. figs) (1 MARK)

c. i. [For every 1 mole of methane combusted at SLC, 24.8 L of greenhouse gas (CO_2) is produced, whereas no greenhouse gas is produced from the combustion of 1 mole of hydrogen gas at SLC.[1]][Therefore, a greater total volume of greenhouse gas is produced from the combustion of methane, compared with that of hydrogen gas.[2]]

I have determined the total volume of greenhouse gas produced from each combustion reaction.[1]

I have determined which combustion reaction produces the greater total greenhouse gas volume.[2]

ii. [The combustion of 1 mole of methane at SLC consumes 24.8 L of greenhouse gas (CH_4) but produces 24.8 L of greenhouse gas (CO_2) resulting in zero net change, whereas the combustion of 1 mole of hydrogen gas at SLC involves no greenhouse gases.[1]][Therefore, the combustion reactions for hydrogen gas and methane gas result in no net change in greenhouse gas volume.[2]]

I have determined the net change in volume of greenhouse gas from each combustion reaction.[1]

I have determined that neither combustion reaction results in a net increase in greenhouse gas volume.[2]

FROM LESSON 1D

2B Calculating energy changes using water

Progress questions

1. D. The change in temperature of water can be used to measure the amount of energy released from a combustion reaction, and hence the fuel or food's heat of combustion.

2. A.

$m(\text{fuel combusted}) = m_{\text{initial}}(\text{fuel + burner}) - m_{\text{final}}(\text{fuel + burner})$

$m(\text{fuel combusted}) = 237.6\ g - 232.2\ g$

$m(\text{fuel combusted}) = 5.4\ g$

3. B. $\Delta T = T_{\text{final}} - T_{\text{initial}}$

$\Delta T = 49.8\ °C - 22.3\ °C$

$\Delta T = 27.5\ °C$

$m(\text{water}) = 200.0\ g$

$c(\text{water}) = 4.18\ J\ g^{-1}\ °C^{-1}$

$q = mc\Delta T$

$q = 200.0\ \text{g} \times 4.18\ \text{J g}^{-1}\ ^\circ\text{C}^{-1} \times 27.5\ ^\circ\text{C}$

$q = 22\ 990\ \text{J}$

$q = 22\ 990 \div 10^3\ \text{kJ}$

$q = 23.0\ \text{kJ}$ (3 sig. figs)

4. D. Calorimeters minimise both the heat loss to the surrounding air (in part by retaining heat in their walls), and the amount of variation in heat loss, making it more consistently measurable.

5. C. $q = VIt$

$q = 6.0\ \text{V} \times 1.3\ \text{A} \times 150\ \text{s}$

$q = 1170\ \text{J}$

$\Delta T = 2.1\ ^\circ\text{C}$

$\text{CF} = \frac{q}{\Delta T}$

$\text{CF} = \frac{1170\ \text{J}}{2.1\ ^\circ\text{C}}$

$\text{CF} = 557.1\ \text{J}\ ^\circ\text{C}^{-1}$

$\text{CF} = 5.6 \times 10^2\ \text{J}\ ^\circ\text{C}^{-1}$ (2 sig. figs)

6. C. The heater was turned on at $t = 200$ seconds. The temperature began decreasing at $t = 500$ seconds. Extrapolation of the line fitting the points from $t = 500$ seconds meets the point $t = 200$ at a temperature of 25.5 °C. Therefore,

$\Delta T = 25.5\ ^\circ\text{C} - 20.0\ ^\circ\text{C}$

$\Delta T = 5.5\ ^\circ\text{C}$

7. B. Option B is a precipitation reaction. Options A, C, and D all are reactions that produce gas and hence cannot be conducted in a solution calorimeter.

Deconstructed

8. A **9.** C

10. B. $q = \text{CF} \times \Delta T$

$q = 140.7\ \text{J}\ ^\circ\text{C}^{-1} \times 8.02\ ^\circ\text{C}$

$q = 1128.4\ \text{J}$

The reaction is exothermic, so ΔH is negative.

$\Delta H = -\frac{q}{n(\text{NaOH})}$

$\Delta H = -\frac{1128.4\ \text{J}}{0.02575\ \text{mol}}$

$\Delta H = -43\ 822\ \text{J mol}^{-1}$

$\Delta H = -43\ 822 \div 10^3\ \text{kJ mol}^{-1}$

$\Delta H = -43.8\ \text{kJ mol}^{-1}$ (3 sig. figs)

Exam-style

11. a. Assuming that 100% of energy released is absorbed by the water:

$q = 1.63 \times 10^3\ \text{kJ}$

$q = 1.63 \times 10^6\ \text{J}$

$m = 100\ \text{kg}$

$m = 1.00 \times 10^5\ \text{g}$

$\Delta T = \frac{q}{m \times c}$ (1 MARK)

$\Delta T = \frac{1.63 \times 10^6\ \text{J}}{(1.00 \times 10^5\ \text{g}) \times 4.18\ \text{J g}^{-1}\ ^\circ\text{C}^{-1}}$

$\Delta T = 3.9\ ^\circ\text{C}$ (1 MARK)

$T_{\text{final}} = T_{\text{initial}} + \Delta T$

$T_{\text{final}} = 25.0\ ^\circ\text{C} + 3.9\ ^\circ\text{C}$

$T_{\text{final}} = 28.9\ ^\circ\text{C}$ (1 MARK)

b. The tank is unlikely to be perfectly insulated, and so some of the energy released from combustion will be lost to the pipes/tank/atmosphere (mainly through conduction and convection), rather than absorbed by the water.

12. D. Options A, B, and C are precipitation, dissolution/ionisation, and neutralisation reactions respectively, all of which can be performed in a solution calorimeter. A solution calorimeter would likely be unable to withstand the high pressures caused by the production of gas from Option D.

13. $q = 1.00 \times 10^3\ \text{GJ}$

$q = 1.00 \times 10^{12}\ \text{J}$ (1 MARK)

$m(\text{H}_2\text{O}) = \frac{q}{c \times \Delta T}$

$m(\text{H}_2\text{O}) = \frac{1.00 \times 10^{12}\ \text{J}}{4.18\ \text{J g}^{-1}\ ^\circ\text{C}^{-1} \times 75.0\ ^\circ\text{C}}$

$m(\text{H}_2\text{O}) = 3.18979 \times 10^9\ \text{g}$ (1 MARK)

$m(\text{H}_2\text{O})$ per kettle $= 1.50\ \text{kg}$ per kettle

$m(\text{H}_2\text{O})$ per kettle $= 1.50 \times 10^3\ \text{g}$ per kettle

$\text{number of kettles} = \frac{m(\text{H}_2\text{O})}{m(\text{H}_2\text{O})\ \text{per kettle}}$

$\text{number of kettles} = \frac{3.18979 \times 10^9\ \text{g}}{1.50 \times 10^3\ \text{g per kettle}}$

number of kettles $= 2\ 130\ 000$ kettles

number of kettles $= 2.13 \times 10^6$ kettles (3 sig. figs) (1 MARK)

14. a. [Calibrating a calorimeter accounts for any heat loss, meaning that the calorimeter does not need to be perfectly insulated.[1]] [This improves the accuracy of results.[2]]

✓ ✗ I have explained that calibration accounts for heat loss.[1]

✓ ✗ I have explained that calibration increases accuracy.[2]

b. Since chemical calibration was used, rather than electrical calibration, extrapolation is not necessary. From the graph,

$\Delta T = T_{\text{final}} - T_{\text{initial}}$

$\Delta T = 28.0\ ^\circ\text{C} - 24.0\ ^\circ\text{C}$

$\Delta T = 4.0\ ^\circ\text{C}$ (1 MARK)

$n(\text{C}_{10}\text{H}_8) = \frac{m}{M}$

$n(\text{C}_{10}\text{H}_8) = \frac{0.212\ \text{g}}{128.0\ \text{g mol}^{-1}}$

$n(\text{C}_{10}\text{H}_8) = 0.001656\ \text{mol}$ (1 MARK)

$q_{\text{absorbed}} = n(\text{C}_{10}\text{H}_8) \times -\Delta H$

$q_{\text{absorbed}} = 0.001656\ \text{mol} \times 5133\ \text{kJ mol}^{-1}$

$q_{\text{absorbed}} = 8.5015\ \text{kJ}$ (1 MARK)

$\text{CF} = \frac{q_{\text{absorbed}}}{\Delta T}$

$$CF = \frac{8.5015\ kJ}{4.0\ °C}$$

$CF = 2.1\ kJ\ °C^{-1}$ or $2100\ J\ °C^{-1}$ (1 MARK)

c. $\Delta T = \frac{q}{CF}$

$$\Delta T = \frac{51.8\ kJ}{2.1\ kJ\ °C^{-1}}$$

$\Delta T = 24\ °C$ (2 sig. figs)

Key science skills

15. a. $q = mc\Delta T$

$q = 500.0\ g \times 4.18\ J\ g^{-1}\ °C^{-1} \times 1.1\ °C$

$q = 2299\ J$

$q = 2.299\ kJ$ (1 MARK)

$$q_{density} = \frac{q}{m(popcorn)}$$

$$q_{density} = \frac{2.299\ kJ}{1.52\ g}$$

$q_{density} = 1.5\ kJ\ g^{-1}$ (1 MARK)

b. $\Delta T = T_{final} - T_{initial}$

$\Delta T = 25.7\ °C - 22.2\ °C$

$\Delta T = 3.5\ °C$

$q = CF \times \Delta T$

$q = 6.54\ kJ\ °C^{-1} \times 3.5\ °C$

$q = 22.89\ kJ$ (1 MARK)

$$q_{density} = \frac{q}{m(popcorn)}$$

$$q_{density} = \frac{22.89\ kJ}{1.50\ g}$$

$q_{density} = 15\ kJ\ g^{-1}$ (2 sig. figs) (1 MARK)

c. i. The calorimetry method produced a more accurate result, as the calculated energy density was closer to the theoretical value.

ii. [A metal calorimeter is better insulated than a glass beaker, leading to less heat energy from combustion being used to heat the surrounding air.[1]][The calorimetry method also accounts for any heat loss by means of calibration, whereas the other method does not account for heat loss.[2]]

✓ ✗ I have explained that a calorimeter has less heat loss than a glass beaker.[1]

✓ ✗ I have explained that the calorimetry method uses calibration to account for heat loss.[2]

d. [Incomplete combustion may have occurred, resulting in less energy being released from the combustion of the popcorn sample.[1]][Popcorn is not a homogeneous substance, so the experimental value for one sample of popcorn may differ from the theoretical value, which is calculated based on the average energy density of this popcorn.[2]]

✓ ✗ I have stated a factor contributing to the inaccuracy.[1]

✓ ✗ I have stated a second factor contributing to the inaccuracy.[2]

Alternative answers:

- Only one trial was carried out, which may mean this disparity results from random error, and would be mitigated through repetition and averaging.
- The popcorn sample may have contained some water, which would have absorbed energy and reduced the amount transferred to the calorimeter.

FROM LESSONS 12B & 12D

Questions from multiple lessons

16. $m(H_2O) = 200.0\ mL \times 1.00\ g\ mL^{-1}$

$m(H_2O) = 200.0\ g$

$\Delta T = T_{final} - T_{initial}$

$\Delta T = 48.5\ °C - 22.0\ °C$

$\Delta T = 26.5\ °C$

Assuming that 100% of energy released is absorbed by the water:

$q = mc\Delta T$

$q = 200.0\ g \times 4.18\ J\ g^{-1}\ °C^{-1} \times 26.5\ °C$

$q = 22\ 154\ J$

$q = 22.154\ kJ$ (1 MARK)

$m(C_2H_6) = 0.500\ g$

$$n(C_2H_6) = \frac{m}{M}$$

$$n(C_2H_6) = \frac{0.500\ g}{30.0\ g\ mol^{-1}}$$

$n(C_2H_6) = 0.01667\ mol$ (1 MARK)

$$\Delta H_{molar} = -\frac{q}{n}$$

$$\Delta H_{molar} = -\frac{22.154\ kJ}{0.01667\ mol}$$

$\Delta H_{molar} = -1.33 \times 10^3\ kJ\ mol^{-1}$ (3 sig. figs)

$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$ (1 MARK)

$\Delta H = -1.33 \times 10^3\ kJ\ (mol^{-1})$ (1 MARK)

Alternative answer:

- $2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(l)$

  $\Delta H = -2.66 \times 10^3\ kJ$

FROM LESSON 1D

17. a. [$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$[1]]
[$\Delta H = -2220\ kJ\ (mol^{-1})$[2]]

✓ ✗ I have written a balanced equation for the complete combustion of propane.[1]

✓ ✗ I have written an appropriate (negative) ΔH value.[2]

b. Theoretical:

$$n(LPG) = \frac{V}{V_m}$$

$$n(LPG) = \frac{0.196\ L}{24.8\ L\ mol^{-1}}$$

$n(LPG) = 0.007903\ mol$ (1 MARK)

If LPG is pure propane,

$n(propane) = n(LPG)$

$n(\text{propane}) = 0.007903 \text{ mol}$

$q_{\text{theoretical}} = n(\text{propane}) \times -\Delta H_{\text{molar}}(\text{propane})$

$q_{\text{theoretical}} = 0.007903 \text{ mol} \times 2220 \text{ kJ mol}^{-1}$

$q_{\text{theoretical}} = 1.75 \times 10^{1} \text{ kJ}$ (1 MARK)

Actual:

$m(H_2O) = 200.0 \text{ g}$

$\Delta T = T_{\text{final}} - T_{\text{initial}}$

$\Delta T = 46.0 \text{ °C} - 25.0 \text{ °C}$

$\Delta T = 21.0 \text{ °C}$

$q_{\text{actual}} = \text{CF} \times \Delta T$

$q_{\text{actual}} = 833 \text{ J °C}^{-1} \times 21.0 \text{ °C}$

$q_{\text{actual}} = 17\,493 \text{ J}$

$q_{\text{actual}} = 1.75 \times 10^{1} \text{ kJ}$ (3 sig. figs) (1 MARK)

Since the calculated energy released by 0.196 L of the LPG is almost exactly equal to the theoretical amount of energy released by 0.196 L of propane, the results suggest that the LPG is pure propane, contradicting Romy's hypothesis. (1 MARK)

FROM LESSONS 1D & 2A

2C Energy from fuels and food

Progress questions

1. D. Chemical energy is stored within a fuel or food, a percentage of which is transformed into harnessable, 'useful' energy.

2. C. $\%\text{ energy efficiency} = \frac{\text{experimental value}}{\text{theoretical value}} \times 100\%$

$\%\text{ energy efficiency} = \frac{288 \text{ kJ}}{459 \text{ kJ}} \times 100\%$

$\%\text{ energy efficiency} = 62.7\%$

3. C. total energy per serving = energy from protein + energy from fat + energy from carbohydrates

total energy per serving = $(2.0 \text{ g} \times 17 \text{ kJ g}^{-1}) + (3.0 \text{ g} \times 37 \text{ kJ g}^{-1}) + (18.7 \text{ g} \times 16 \text{ kJ g}^{-1})$

total energy per serving = 444.2 kJ

total energy per serving = 4.4×10^{2} kJ

Deconstructed

4. B **5.** C

6. theoretical $q = m(\text{butane}) \times 49.7 \text{ kJ g}^{-1}$

theoretical $q = 1.68 \text{ g} \times 49.7 \text{ kJ g}^{-1}$

theoretical $q = 83.496$ kJ

$\Delta T = 39.40 \text{ °C} - 22.14 \text{ °C}$

$\Delta T = 17.26 \text{ °C}$ (1 MARK)

experimental $q = m(\text{water}) \times c \times \Delta T$

experimental $q = 100.0 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ °C}^{-1} \times 17.26 \text{ °C}$

experimental $q = 7214.7$ J

experimental $q = 7.2147$ kJ (1 MARK)

$\text{percentage energy efficiency} = \frac{\text{experimental } q}{\text{theoretical } q} \times 100\%$

$\text{percentage energy efficiency} = \frac{7.2147 \text{ kJ}}{83.496 \text{ kJ}} \times 100\%$

percentage energy efficiency = 8.64% (1 MARK)

Exam-style

7. total energy per 100 g = energy from digestible carbohydrates + energy from protein + energy from fats

total energy per 100 g = $(1.8 \text{ g} \times 16 \text{ kJ g}^{-1}) + (2.0 \text{ g} \times 17 \text{ kJ g}^{-1}) + (14.7 \text{ g} \times 37 \text{ kJ g}^{-1})$ (1 MARK)

total energy per 100 g = 606.7 kJ

total energy per 100 g = 6.1×10^{2} kJ (2 sig. figs) (1 MARK)

8. a. $n(C_2H_5OH) = \frac{m}{M}$

$n(C_2H_5OH) = \frac{1.80 \text{ g}}{46.0 \text{ g mol}^{-1}}$

$n(C_2H_5OH) = 0.03913$ mol (1 MARK)

energy released by ethanol = $n(C_2H_5OH) \times$ molar heat of combustion of ethanol

energy released by ethanol = $0.03913 \text{ mol} \times 1360 \text{ kJ mol}^{-1}$

energy released by ethanol = 53.2174 kJ (1 MARK)

energy absorbed by water = $m(H_2O) \times c(H_2O) \times \Delta T(H_2O)$

energy absorbed by water = $100.0 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ °C}^{-1} \times (40.0 \text{ °C} - 25.0 \text{ °C})$

energy absorbed by water = 6.27×10^{3} J

energy absorbed by water = 6.27 kJ (1 MARK)

energy not absorbed by water = 53.2174 kJ − 6.27 kJ

energy not absorbed by water = 46.9474 kJ

$\%\text{ heat lost} = \frac{\text{energy not absorbed}}{\text{energy released}} \times 100\%$

$\%\text{ heat lost} = \frac{46.9474 \text{ kJ}}{53.2174 \text{ kJ}} \times 100\%$

% heat lost = 88.2% (3 sig. figs) (1 MARK)

b. Insulate the side of the can/put a lid or cover on the can/put a protective sleeve around the burner to reduce heat loss to the surroundings

9. a. total energy = energy from protein + energy from carbohydrates + energy from fat

total energy = $(17 \text{ kJ g}^{-1} \times 9.8 \text{ g}) + (16 \text{ kJ g}^{-1} \times 20.0 \text{ g}) + (37 \text{ kJ g}^{-1} \times 7.0 \text{ g})$

total energy = 166.6 kJ + 320 kJ + 259 kJ

total energy = 745.6 kJ

total energy = 7.5×10^{2} kJ (2 sig. figs) (1 MARK)

Therefore, the bar contains approximately 750 kJ of energy, which is less than 800 kJ, and so the bar meets Penny's energy requirements. (1 MARK)

b. mass of a bar = 9.8 g + 20.0 g + 3.2 g + 7.0 g

mass of a bar = 40.0 g (1 MARK)

$$\text{energy per 100 g} = \text{total energy per bar} \times \frac{100\text{ g}}{\text{mass of a bar}}$$

$$\text{energy per 100 g} = 745.6\text{ kJ} \times \frac{100\text{ g}}{40.0\text{ g}}$$

energy per 100 g = 1864 kJ per 100 g

energy per 100 g = 1.9×10^3 kJ (2 sig. figs) (1 MARK)

c. $$\%\text{ of energy from butter} = \frac{\text{energy from butter}}{\text{total energy}} \times 100\%$$

$$\%\text{ of energy from butter} = \frac{37\text{ kJ g}^{-1} \times 7.0\text{ g}}{745.6\text{ kJ}} \times 100\%$$

% of energy from butter = 34.7%

% of energy from butter = 35% (2 sig. figs)

10. energy from carbohydrates = 16 kJ g^{-1} × 21.3 g

energy from carbohydrates = 340.8 kJ

energy from fat = 37 kJ g^{-1} × 16.5 g

energy from fat = 610.5 kJ

energy from protein = total energy − energy from carbohydrates − energy from fat

energy from protein = 1022.7 kJ − 340.8 kJ − 610.5 kJ

energy from protein = 71.4 kJ (1 MARK)

$$\text{mass of protein} = \frac{\text{energy from protein}}{\text{energy density of protein}}$$

$$\text{mass of protein} = \frac{71.4\text{ kJ}}{17\text{ kJ g}^{-1}}$$

mass of protein = 4.2 g (2 sig. figs) (1 MARK)

Therefore, a bar only contains 4.2 g of protein, which is less than 5 g, and so the company's statement is inaccurate. (1 MARK)

11. D. For 100% efficiency:

$$m(C_8H_{18}) = \frac{\text{energy used}}{\text{energy from 1 g}}$$

$$m(C_8H_{18}) = \frac{528 \times 10^3\text{ kJ}}{47.9\text{ kJ g}^{-1}}$$

$m(C_8H_{18}) = 1.1023 \times 10^4$ g

$d = \frac{m}{V}$

$V = \frac{m}{d}$

$$V_{\text{theoretical}}(C_8H_{18}) = \frac{1.1023 \times 10^4\text{ g}}{703\text{ g L}^{-1}}$$

$V_{\text{theoretical}}(C_8H_{18}) = 15.68$ L

Since the reaction when octane undergoes combustion is only 25% efficient, 15.68 L is only 25% of the octane consumed.

$$V_{\text{actual}} = \frac{V_{\text{theoretical}}}{\text{efficiency}}$$

$$V_{\text{actual}}(C_8H_{18}) = \frac{15.68\text{ L}}{0.25}$$

$V_{\text{actual}}(C_8H_{18}) = 62.7$ L (3 sig. figs)

Key science skills

12. a. i. Light a spirit burner containing ethanol under the beaker and measure the water's temperature change.

ii. Place the corn chip on a watch glass on a stand below the beaker, light it using a match, and measure the water's temperature change.

b. i. Hot water and glass falling from the tripod can cause burns or cuts/naked flames can burn the skin/black soot can stain clothing and skin.

ii. The corn chip must be secured while burning to reduce risk of fire and burns/hot dripping oil falling onto skin when the chip is burning can cause burns.

c. Ethanol:

From the VCE Data Book, energy per gram = 29.6 kJ g^{-1}

energy per 100 g = 29.6 kJ g^{-1} × 100 g

energy per 100 g = 2.96×10^3 kJ (3 sig. figs) (1 MARK)

Corn chips:

total energy per 100 g = energy from carbohydrates + energy from protein + energy from fats

total energy per 100 g = (59.4 g × 16 kJ g^{-1}) + (6.3 g × 17 kJ g^{-1}) + (26.6 g × 37 kJ g^{-1})

total energy per 100 g = 2041.7 kJ

total energy per 100 g = 2.0×10^3 kJ (2 sig. figs) (1 MARK)

Therefore, based on theoretical values, ethanol contains more energy per 100 g than corn chips. (1 MARK)

FROM LESSON 12B

Questions from multiple lessons

13. a. $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$

b. Since glucose is a carbohydrate, the energy released from cellular respiration is equivalent to the heat of combustion of carbohydrates (16 kJ g^{-1}). (1 MARK)

energy produced = heat of combustion of glucose × mass of glucose

energy produced = 16 kJ g^{-1} × 4.3 g

energy produced = 68.8 kJ

energy produced = 6.9×10^1 kJ (2 sig. figs) (1 MARK)

FROM LESSON 1C

14. a. theoretical energy from CH_4 = $m(CH_4)$ × energy density of CH_4

theoretical energy from CH_4 = 0.485 g × 55.6 kJ g^{-1}

theoretical energy from CH_4 = 26.966 kJ (1 MARK)

energy absorbed by water = $m(H_2O) \times c(H_2O) \times \Delta T(H_2O)$

energy absorbed by water = 350.0 g × 4.18 J g^{-1} $°C^{-1}$ × (32.3 °C − 20.0 °C)

energy absorbed by water = 1.7995×10^4 J

energy absorbed by water = 17.995 kJ (1 MARK)

$$\%\text{ energy absorbed} = \frac{\text{energy absorbed by water}}{\text{theoretical energy produced}} \times 100\%$$

$$\%\text{ energy absorbed} = \frac{17.995\text{ kJ}}{26.966\text{ kJ}} \times 100\%$$

% energy absorbed = 66.7% (3 sig. figs) (1 MARK)

b. i. The results will likely be inaccurate because this setup is not 100% efficient at transferring heat energy.

ii. [Repeat the initial experiment using CH_4 over multiple trials, and hence obtain an average value for the efficiency of the setup (a form of chemical calibration).[1]] [Determine the amount of energy absorbed by the water when a given quantity of the unknown fuel is combusted in this setup.[2]] [Divide this quantity of energy by the setup's average efficiency to obtain an 'adjusted' value for energy, and hence estimate the unknown fuel's heat of combustion.[3]]

✓ ✗ I have suggested repetition of the calibration step to improve accuracy.[1]

✓ ✗ I have suggested calculation of the experimental value for energy absorbed, using the unknown fuel.[2]

✓ ✗ I have suggested adjustment of the experimental value using the calculated efficiency.[3]

FROM LESSON 2B

Chapter 2 review

Multiple choice

1. C. mass of carbohydrates per 100 g serving $= 100\text{ g} \times \frac{45\%}{100\%}$

mass of carbohydrates per 100 g serving $= 45\text{ g}$

energy from carbohydrates per 100 g serving $= 45\text{ g} \times 16\text{ kJ g}^{-1}$

energy from carbohydrates per 100 g serving $= 720\text{ kJ}$

2. D. $q = VIt$

$q = 3.8\text{ V} \times 1.8\text{ A} \times 200\text{ s}$

$q = 1400\text{ J}$

3. A. $q = \text{CF} \times \Delta T$

$q = 760\text{ J °C}^{-1} \times 29.6\text{ °C}$

$q = 22\,496\text{ J}$

$\text{molar heat of solution of NaOH} = \frac{q}{n(\text{NaOH})}$

$\text{molar heat of solution of NaOH} = \frac{22\,496\text{ J}}{0.50\text{ mol}}$

$\text{molar heat of solution of NaOH} = 44\,992\text{ J mol}^{-1}$

$\text{molar heat of solution of NaOH} = 44.992\text{ kJ mol}^{-1}$

The reaction is exothermic, so ΔH is negative.

$\Delta H = -45\text{ kJ mol}^{-1}$ (2 sig. figs)

4. B. total energy = energy from protein + energy from fat + energy from carbohydrates

total energy $= (17\text{ kJ g}^{-1} \times 3.3\text{ g}) + (37\text{ kJ g}^{-1} \times 12.9\text{ g}) + (16\text{ kJ g}^{-1} \times 29.2\text{ g})$

total energy $= 56.1\text{ kJ} + 477.3\text{ kJ} + 467.2\text{ kJ}$

total energy $= 1000.6\text{ kJ}$

total energy $\approx 1000\text{ kJ}$

5. C. $q = m(\text{ethanol}) \times \Delta H_{\text{mass}}(\text{ethanol})$

$q = 3.00\text{ g} \times 3.02\text{ kJ g}^{-1}$

$q = 9.06\text{ kJ}$

$q = 9.06 \times 10^3\text{ J}$

$\Delta T = \frac{q}{m \times c}$

$\Delta T = \frac{9.06 \times 10^3\text{ J}}{100.0\text{ g} \times 4.18\text{ J g}^{-1}\text{ °C}^{-1}}$

$\Delta T = 21.675\text{ °C}$

$T_{\text{final}} = 20.6\text{ °C} + 21.675\text{ °C}$

$T_{\text{final}} = 42.3\text{ °C}$ (3 sig. figs)

6. B. From the VCE Data Book, heat of combustion of ethanol = 29.6 kJ g^{-1}

$\%\text{ energy efficiency} = \frac{\text{experimental heat of combustion}}{\text{theoretical heat of combustion}} \times 100\%$

$\%\text{ energy efficiency} = \frac{3.02\text{ kJ g}^{-1}}{29.6\text{ kJ g}^{-1}} \times 100\%$

$\%\text{ energy efficiency} = 10.2\%$ (3 sig. figs)

7. A. A well-insulated calorimeter will generally lead to more consistent heat loss to the environment and apparatus, leading to more consistent and hence more precise results. The use of a calibration factor adjusts for inaccuracy due to heat loss, producing more accurate results.

8. B. From graph, $\Delta T \approx 21.2\text{ °C} - 18.0\text{ °C}$

$\Delta T \approx 3.2\text{ °C}$

$q = VIt$

$q = 5.4\text{ V} \times 2.7\text{ A} \times 180\text{ s}$

$q = 2624.4\text{ J}$

$\text{CF} = \frac{q}{\Delta T}$

$\text{CF} \approx \frac{2624.4\text{ J}}{3.2\text{ °C}}$

$\text{CF} \approx 820\text{ J °C}^{-1}$

9. D. Option A: Heat loss is evident on the graph, as the temperature drops from 21.2 °C.

Option B: Solution calorimeters are not suitable for combustion reactions as these reactions produce gases.

Option C: Any calorimeter can be calibrated using chemical reactions with known heats of reaction.

Option D: Calibration factor generally only needs to be calculated once per calorimeter per laboratory sitting.

10. D. Since $q = mc\Delta T$, a smaller volume of water added for the reaction (smaller m) results in a greater change in temperature (since q is constant). Hence the calculated energy released ($\text{CF} \times \Delta T$) is larger, resulting in a higher calculated molar heat of solution $\left(\frac{\text{energy released}}{n(\text{NH}_4\text{NO}_3)}\right)$.

Short answer

11. a. $[C_2H_2(g) + \frac{5}{2}O_2(g) \rightarrow 2CO_2(g) + H_2O(l)^1]$
$[\Delta H = -1300 \text{ kJ (mol}^{-1})^2]$

✓ ✗ I have written a balanced equation for the combustion of ethyne at SLC.[1]

✓ ✗ I have given an appropriate value for the enthalpy change of this reaction.[2]

Alternative answer:

- $2C_2H_2(g) + 5O_2(g) \rightarrow 4CO_2(g) + 2H_2O(l) \quad \Delta H = -2600 \text{ kJ}$

b. $n(C_2H_2) = \frac{V}{V_m}$

$n(C_2H_2) = \frac{200.0 \text{ L}}{24.8 \text{ L mol}^{-1}}$

$n(C_2H_2) = 8.0645 \text{ mol}$ (1 MARK)

$n(CO_2) : n(C_2H_2)$

2 : 1

$n(CO_2) = \frac{2}{1} \times n(C_2H_2)$

$n(CO_2) = \frac{2}{1} \times 8.0645 \text{ mol}$

$n(CO_2) = 16.1 \text{ mol (3 sig. figs)}$ (1 MARK)

c. energy = 25 MJ

energy = 2.5×10^4 kJ

$n(C_2H_2) = \frac{\text{energy}}{\text{molar heat of combustion of } C_2H_2}$

$n(C_2H_2) = \frac{2.5 \times 10^4 \text{ kJ}}{1300 \text{ kJ mol}^{-1}}$

$n(C_2H_2) = 19.23 \text{ mol}$ (1 MARK)

$m(C_2H_2) = n \times M$

$m(C_2H_2) = 19.23 \text{ mol} \times 26.0 \text{ g mol}^{-1}$

$m(C_2H_2) = 500 \text{ g}$

$m(C_2H_2) = 0.50 \text{ kg (2 sig. figs)}$ (1 MARK)

d. $m(H_2O) = V(H_2O) \times d(H_2O)$

$m(H_2O) = 500.0 \text{ mL} \times 0.997 \text{ g mL}^{-1}$

$m(H_2O) = 498.5 \text{ g}$ (1 MARK)

$q = 112.5 \text{ kJ}$

$q = 1.125 \times 10^5 \text{ J}$ (1 MARK)

$\Delta T = \frac{q}{mc}$

$\Delta T = \frac{1.125 \times 10^5 \text{ J}}{498.5 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ °C}^{-1}}$

$\Delta T = 53.99 \text{ °C}$ (1 MARK)

$T_{initial} = 25.0 \text{ °C (at SLC)}$

$T_{final} = T_{initial} + \Delta T$

$T_{final} = 25.0 \text{ °C} + 53.99 \text{ °C}$

$T_{final} = 79.0 \text{ °C (3 sig. figs)}$ (1 MARK)

12. a. energy = energy from protein + energy from fats and oils

energy = $(17 \text{ kJ g}^{-1} \times 9.1 \text{ g}) + (37 \text{ kJ g}^{-1} \times 2.5 \text{ g})$

energy = 154.7 kJ + 92.5 kJ

energy = 2.5×10^2 kJ (2 sig. figs)

b. i. energy transferred to water = $m(H_2O) \times c(H_2O) \times \Delta T(H_2O)$

energy transferred to water = $200 \text{ g} \times 4.18 \text{ J g}^{-1} \text{ °C}^{-1} \times 6 \text{ °C}$

energy transferred to water = 5.016×10^3 J

energy transferred to water = 5.016 kJ (1 MARK)

energy per gram of bread = $\frac{1000 \text{ kJ}}{100 \text{ g}}$

energy per gram of bread = 10 kJ g^{-1}

mass of bread = $\frac{\text{energy transferred to water}}{\text{energy per gram of bread}}$

mass of bread = $\frac{5.016 \text{ kJ}}{10 \text{ kJ g}^{-1}}$

mass of bread = 0.5 g (1 sig. fig.) (1 MARK)

ii. From part **i**, theoretical mass of bread required to raise the temperature of the water by 6 °C = 0.5016 g

% efficiency = $\frac{\text{theoretical mass of bread required}}{\text{actual mass of bread required}} \times 100\%$

% efficiency = $\frac{0.5016 \text{ g}}{1.2 \text{ g}} \times 100\%$

% efficiency = 41.8%

% efficiency = 42% (2 sig. figs)

13. energy in 100 g of bananas = energy from protein + energy from carbohydrates + energy from fat

energy in 100 g of bananas = $(1.1 \text{ g} \times 17 \text{ kJ g}^{-1}) + (22.8 \text{ g} \times 16 \text{ kJ g}^{-1}) + (0.30 \text{ g} \times 37 \text{ kJ g}^{-1})$

energy in 100 g of bananas = 18.7 kJ + 364.8 kJ + 11.1 kJ

energy in 100 g of bananas = 394.6 kJ (1 MARK)

energy from one banana = $\frac{\text{energy in 100 g of bananas}}{100 \text{ g}} \times \text{mass of one banana}$

energy from one banana = $\frac{394.6 \text{ kJ}}{100 \text{ g}} \times 116 \text{ g}$

energy from one banana = 457.736 kJ (1 MARK)

number of bananas = $\frac{\text{total energy}}{\text{energy from one banana}}$

number of bananas = $\frac{300 \text{ kJ}}{457.736 \text{ kJ}}$

number of bananas = 0.6554

number of bananas = 0.66 (2 d.p.) (1 MARK)

14. $V(O_2) = 19.6 \text{ mL}$

$V(O_2) = 0.0196 \text{ L}$

$n(O_2) = \frac{V}{V_m}$ (at SLC)

$n(O_2) = \frac{0.0196 \text{ L}}{24.8 \text{ L mol}^{-1}}$

$n(O_2) = 7.9032 \times 10^{-4} \text{ mol}$ (1 MARK)

$n(C_6H_{12}O_6) : n(O_2)$

1 : 6

$n(C_6H_{12}O_6) = \frac{1}{6} \times n(O_2)$

$n(C_6H_{12}O_6) = 1.3712 \times 10^{-4}$ mol (1 MARK)

energy produced $= -\Delta H_{molar} \times n(C_6H_{12}O_6)$

energy produced $= 2816$ kJ mol$^{-1} \times (1.3712 \times 10^{-4}$ mol)

energy produced $= 3.71 \times 10^{-1}$ kJ (3 sig. figs) (1 MARK)

15. Biscuit 1:

mass of digestible carbohydrates = total mass of carbohydrates − mass of dietary fibre

mass of digestible carbohydrates = 22.0 g − 2.5 g

mass of digestible carbohydrates = 19.5 g

total energy = energy density of protein × mass of protein + energy density of fat × mass of fats + energy density of carbohydrate × mass of digestible carbohydrates

total energy = (17 kJ g^{-1} × 6.8 g) + (37 kJ g^{-1} × 18.7 g) + (16 kJ g^{-1} × 19.5 g)

total energy = 1119.5 kJ

total energy = 1.1×10^3 kJ (2 sig. figs) (1 MARK)

Biscuit 2:

mass of digestible carbohydrates = total mass of carbohydrates − mass of dietary fibre

mass of digestible carbohydrates = 22.0 g − 1.6 g

mass of digestible carbohydrates = 20.4 g

total energy = energy density of protein × mass of protein + energy density of fat × mass of fats + energy density of carbohydrate × mass of digestible carbohydrates

total energy = (17 kJ g^{-1} × 7.3 g) + (37 kJ g^{-1} × 19.1 g) + (16 kJ g^{-1} × 20.4 g)

total energy = 1157.2 kJ

total energy = 1.2×10^3 kJ (2 sig. figs) (1 MARK)

Therefore, Biscuit 2 contains more energy per serving than Biscuit 1. (1 MARK)

16. a. At SLC, CO_2 is the only greenhouse gas produced. (1 MARK)

$V(CO_2) : V(C_4H_{10})$

8 : 2

$V(CO_2) = \frac{8}{2} \times V(C_4H_{10})$

$V(CO_2) = \frac{8}{2} \times 80.0$ L

$V(CO_2) = 320$ L

Therefore, 320 L of greenhouse gas is produced. (1 MARK)

b. $n(C_4H_{10}) = \frac{V}{V_m}$

$n(C_4H_{10}) = \frac{80.0 \text{ L}}{24.8 \text{ L mol}^{-1}}$

$n(C_4H_{10}) = 3.2258$ mol (1 MARK)

$n(H_2O) : n(C_4H_{10})$

10 : 2

$n(H_2O) = \frac{10}{2} \times n(C_4H_{10})$

$n(H_2O) = \frac{10}{2} \times 3.2258$ mol

$n(H_2O) = 16.129$ mol (1 MARK)

$m(H_2O) = n(H_2O) \times M(H_2O)$

$m(H_2O) = 16.129$ mol $\times$ 18.0 g mol^{-1}

$m(H_2O) = 290.3$ g

$m(H_2O) = 2.90 \times 10^2$ g (3 sig. figs) (1 MARK)

c. From part **b**, $n(C_4H_{10}) = 3.2258$ mol

In the thermochemical equation given, the ΔH value corresponds with the combustion of 2 mol of C_4H_{10}.

theoretical energy $= \frac{n(C_4H_{10})}{2 \text{ mol}} \times -\Delta H$

theoretical energy $= \frac{3.2258 \text{ mol}}{2 \text{ mol}} \times 5750$ kJ

theoretical energy = 9274 kJ (1 MARK)

% energy efficiency $= \frac{\text{actual energy}}{\text{theoretical energy}} \times 100\%$

% energy efficiency $= \frac{5.0 \times 10^3 \text{ kJ}}{9274 \text{ kJ}} \times 100\%$

% energy efficiency = 53.9%

% energy efficiency = 54% (2 sig. figs) (1 MARK)

Key science skills

17. a. Method of calibration

b. Inaccurately calibrated voltmeter/ammeter/power supply or consistent energy loss across electrical connections

c. The graph does not show the temperature of the water prior to the power source being switched on, although this was measured.

Alternative answers:

- The graph only shows the water temperature for a total of 540 seconds during and after the time the power was on, although the method states that the temperature was measured for a total of 600 seconds during and after the time the power was on.
- The graph does not show the water temperature after 30 seconds or after 90 seconds, yet the temperature was supposedly measured at 30-second intervals.

d. [The water temperature was not allowed to stabilise before chemical calibration began.[1]][To address this, the water temperature should be measured (until stabilisation is observed) prior to adding KNO_3 to the calorimeter.[2]]

✓ ✗ I have identified a limitation of the chemical calibration method.[1]

✓ ✗ I have suggested a way to address this limitation.[2]

e. $n(KNO_3) = \frac{m}{M}$

$n(KNO_3) = \frac{3.0 \text{ g}}{101.1 \text{ g mol}^{-1}}$

$n(KNO_3) = 0.02967$ mol (1 MARK)

theoretical energy absorbed = $n(KNO_3) \times \Delta H$ of KNO_3 dissolution

theoretical energy absorbed = 0.02967 mol $\times$ +35 kJ mol^{-1}

theoretical energy absorbed = 1.04 kJ (1 MARK)

ΔT (from graph) = 22.0 °C − 23.6 °C

ΔT (from graph) = −1.6 °C (allow −1.5 °C to −1.7 °C)

$$\text{CF} = \frac{\text{theoretical energy absorbed}}{-\Delta T}$$

(for chemical calibration using an endothermic reaction)

$$\text{CF} = \frac{1.04\ \text{kJ}}{1.6\ °\text{C}}$$

CF = 0.65 kJ $°C^{-1}$ (2 sig. figs)

CF = 6.5×10^2 J $°C^{-1}$ (1 MARK)

(allow 6.1×10^2 J $°C^{-1}$ to 6.9×10^2 J $°C^{-1}$)

f. [This calibration factor is associated with a solution calorimeter, which is not suitable for a combustion reaction.[1]][This calibration factor was calculated based on an endothermic reaction, making it likely inaccurate for an exothermic reaction (such as combustion).[2]]

✓ ✗ I have explained a first issue with the suggestion.[1]

✓ ✗ I have explained a second issue with the suggestion.[2]

FROM LESSONS 12C, 12D & 12E

3A Redox reactions

Progress questions

1. A. The magnesium atom loses two electrons during the oxidation reaction.

2. B. A conjugate redox pair consists of an oxidising/reducing agent (reactant) and the species formed when this reactant is reduced/oxidised (product).

3. B. Reducing agents are oxidised, and so they lose one or more electrons.

4. B. The overall charge of this ion is −4, and the oxidation state of an oxygen atom in a compound is normally −2. Therefore, 2 × oxidation state of each phosphorus atom + 7 × oxidation state of each oxygen atom = −4

Let x represent the oxidation state of each phosphorus atom.

$2 \times x + 7 \times (-2) = -4$

$2x = +10$

$x = +5$

Therefore, the oxidation state of each phosphorus atom is +5.

5. D. An increase in oxidation number indicates that a species has been oxidised. In equation D, the oxidation state of aluminium is initially 0, then increases to +3. Therefore, oxidation has occurred.

Deconstructed

6. C **7.** A

8. [A reducing agent undergoes oxidation in a redox reaction, which causes its oxidation number to increase. In this reaction, the oxidation state of iron increases from 0 to +3, as it loses 3 electrons.[1]][Therefore, Fe(s) is the reducing agent.[2]]

✓ ✗ I have explained that the oxidation numbers of a reducing agent increase during redox reactions.[1]

✓ ✗ I have identified the reducing agent in this reaction.[2]

Exam-style

9. D. Hydrogen and oxygen atoms in chemical compounds usually have oxidation states of +1 and −2 respectively. Aluminium is a group 13 metal that takes an oxidation state of +3. Therefore, the oxidation state of sulfur is +6 in SO_3 and HSO_4^-, +4 in SO_2 and −2 in Al_2S_3.

10. C. Equation B involves the loss of electrons (electrons are on the product side), and hence represents an oxidation reaction. Hydrogen atoms are unbalanced in equation A and oxygen atoms are unbalanced in equation D. Therefore, options B, A, and D are incorrect.

11. [No,[1]][as there is no change in the oxidation state of any of the species in this reaction.[2]]

✓ ✗ I have identified whether this equation represents a redox reaction.[1]

✓ ✗ I have justified my answer with reference to oxidation states.[2]

12. a. H_2SO_4 has no overall charge, so the sum of the oxidation states of each of its atoms will be 0. The oxidation state of hydrogen and oxygen atoms in compounds are normally +1 and −2 respectively.

Let x represent the oxidation state of sulfur.

$2 \times 1 + x + 4 \times (-2) = 0$

$x = +6$

Therefore, the oxidation state of sulfur in H_2SO_4 is +6.

b. All species (H, N, S, and O)

c. No. There is no change in the oxidation numbers of any species in this reaction.

13. a. A species loses electrons during oxidation reactions, where its oxidation state increases. The oxidation state of hydrogen increases from 0 to +1 during this reaction. This increase in positive charge can be thought of as a loss of negative charge. Therefore, $H_2(g)$ loses electrons.

b. $H_2(g)$ and $H^+(aq)$. This pair includes the reducing agent, $H_2(g)$, and the species formed when it is oxidised, $H^+(aq)$.

c. Oxidising agents undergo reduction, meaning their oxidation numbers decrease during redox reactions. The oxidation state of chlorine decreases from 0 to −1 during this reaction. Therefore, $Cl_2(g)$ is the oxidising agent.

d. $Cl_2(g)$ forms a conjugate redox pair with $Cl^-(aq)$. Cl^- is a simple ion with charge −1. Therefore, its oxidation state is −1.

14. a. [Each zinc atom as Zn(s) has an oxidation number of 0. This number increases during the reaction, as zinc has an oxidation number of +2 in ZnO(s) in the products. This increase in oxidation number means that zinc has lost negative charge.[1]][Therefore, Zn(s) has lost 2 electrons and undergone oxidation.[2]]

✓ ✗ I have identified which element's oxidation number increases.[1]

✓ ✗ I have stated which element has been oxidised, with reference to a loss of electrons.[2]

b. Oxidising agents undergo reduction during redox reactions, meaning their oxidation number decreases. During this reaction, the oxidation state of oxygen decreases from 0 to −2. Therefore, $O_2(g)$ is the oxidising agent.

Key science skills

15. a. [The wire will gain mass.[1]][Silver atoms are gained at double the rate that copper cations are lost, and silver has a greater molar mass than copper. This means that the rate that the wire gains mass is greater than the rate it loses mass. (Note that the mass of electrons is negligible.)[2]]

✓ ✗ I have stated whether the wire gains or loses mass.[1]

✓ ✗ I have justified my answer with reference to the molar masses of silver and copper, as well as the number of silver atoms gained for every copper ion lost.[2]

b. Mass of silver gained per mole of copper lost = $n(\text{Ag}) \times M(\text{Ag})$

Mass of silver gained per mole of copper lost = 2 mol × 107.9 g mol^{-1}

Mass of silver gained per mole of copper lost = 215.8 g (1 MARK)

Mass of one mole of copper lost:
$m = n(\text{Cu}^+) \times M(\text{Cu}^+)$

$m = 1 \text{ mol} \times 63.5 \text{ g mol}^{-1}$

$m = 63.5$ g (1 MARK)

Change in mass per mole of copper lost:
m = mass of silver gained − mass of copper lost

$m = 215.8 \text{ g} - 63.5 \text{ g}$

$m = 152.3$ g (1 MARK)

c. [Noor is correct.[1]][The mass that the wire has gained comes from silver cations from the $AgNO_3$ solution, which have lost electrons to form solid silver. Similarly, solid copper lost from the wire forms copper cations that are released into the solution. This means that the solution loses mass, offsetting the mass gained by the wire.[2]][This reaction involves only a transfer of electrons between species. Therefore, the reactants and the products contain the same number of protons, neutrons and electrons. All reactants and products are either in a solid or liquid state, so there is no opportunity for them to escape the beaker, and so there should be no change in the mass of the system during this reaction.[3]]

- I have correctly identified whose statement is correct.[1]
- I have explained why Kiran's statement is incorrect.[2]
- I have explained why Noor's statement is correct.[3]

d. [A change in temperature between trials could have caused this.[1]][This variable (temperature) must be controlled in order for this experiment and its results to be valid.[2]]

- I have identified a factor that could influence the experimental results.[1]
- I have explained the effect this has on the validity of the experiment.[2]

FROM LESSONS 12B & 12D

Questions from multiple lessons

16. a. $C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$

b. [During combustion reactions, oxygen oxidises a fuel. In this case, $O_2(g)$ is reduced, as its average oxidation state decreases from 0 to −2.[1]][and the carbon in $C_3H_8(g)$ is oxidised, as its average oxidation state increases from $-\frac{8}{3}$ to +4.[2]]

- I have identified the species that is reduced using oxidation states.[1]
- I have identified the species that is oxidised using oxidation states.[2]

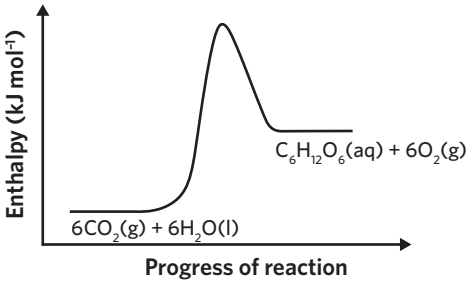
FROM LESSON 1D

17. a. [Yes.[1]][The average oxidation state of carbon decreases during the reaction (+4 in CO_2 to 0 in $C_6H_{12}O_6$) and the oxidation state of oxygen increases during the reaction (−2 in CO_2 to 0 in O_2). Therefore, a redox reaction has occurred.[2]]

- I have identified whether photosynthesis is a redox reaction.[1]
- I have justified my answer with reference to changes in oxidation states.[2]

b. Endothermic. There is a net absorption of energy during this reaction as light energy (from surroundings) is converted into chemical energy (bond energy).

c.



FROM LESSONS 1C & 1D

3B Writing redox equations

Progress questions

1. A. To balance this equation, electrons must be added so that the charges on each side of the equation are equal. In the unbalanced equation, the reactants have a charge of +2 and the products have a charge of +4. Therefore, 2 electrons must be added to the products so that each side of the equation has an overall charge of +2.

2. B. H^+ ions are present in equations A and D, so they must occur in acidic rather than basic conditions. Equation C shows the oxidation of $Mn^{2+}(aq)$ to $MnO_4^-(aq)$, which is the reverse reaction of the reaction described in the question. Therefore, answers A, C and D are incorrect.

3. C. Equations B and D represent reduction reactions, as electrons are only present in the reactants and are gained by SO_4^{2-}, so are incorrect. Equation A is unbalanced.

4. C. In order for these two half-equations to be added together to form the overall redox equation, the coefficients of the oxidation half-equation must be doubled, so that each equation has the same number of electrons.

5. C. This is a redox half-equation because only reduction occurs during this reaction; the oxidation number of Cr decreases (+6 to +3), whereas the oxidation numbers of all other species remain the same.

Deconstructed

6. D **7.** B

8. [Oxidation: $Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$[1]][Reduction: $MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 4H_2O(l)$[2]][Overall: $5Fe^{2+}(aq) + MnO_4^-(aq) + 8H^+(aq) \rightarrow 5Fe^{3+}(aq) + Mn^{2+}(aq) + 4H_2O(l)$[3]]

✓ ✗ I have balanced the oxidation half-equation using KOHES.[1]

✓ ✗ I have balanced the reduction half-equation using KOHES.[2]

✓ ✗ I have combined the two half-equations.[3]

Exam-style

9. C. The oxidation half-equation must have electrons present in the products to show a loss of electrons and must not contain the oxidising agent (O_2).

10. a. $H_2O_2(aq) + 2H^+(aq) + 2e^- \rightarrow 2H_2O(l)$

b. $2NH_4^+(aq) \rightarrow N_2(g) + 8H^+(aq) + 6e^-$

11. a. [Oxidation: $CH_3OH(l) + H_2O(l) \rightarrow 4H^+(aq) + 4e^- + HCOOH(l)$[1]] [Reduction: $Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \rightarrow 2Cr^{3+}(aq) + 7H_2O(l)$[2]]

✓ ✗ I have labelled a balanced oxidation half-equation.[1]

✓ ✗ I have labelled a balanced reduction half-equation.[2]

b. The lowest common multiple of 6 (×2) and 4 (×3) is 12.

Oxidation:
$3 \times (CH_3OH(l) + H_2O(l) \rightarrow HCOOH(aq) + 4H^+(aq) + 4e^-)$

Reduction:
$2 \times (Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \rightarrow 2Cr^{3+}(aq) + 7H_2O(l))$

Overall:
$3CH_3OH(l) + 2Cr_2O_7^{2-}(aq) + 16H^+(aq) \rightarrow 3HCOOH(aq) + 4Cr^{3+}(aq) + 11H_2O(l)$

12. a. $Zn + 2OH^- \rightarrow Zn(OH)_2 + 2e^-$

b. $Ag_2O + H_2O + 2e^- \rightarrow 2Ag + 2OH^-$

c. $Ag_2O + Zn + H_2O \rightarrow 2Ag + Zn(OH)_2$

13. a. $CH_3CH_2OH \rightarrow CH_3CHO + 2H^+ + 2e^-$

b. $NAD^+ + H^+ + 2e^- \rightarrow NADH$

14. C. This equation can be balanced by separating it into its half-equations.

Unbalanced reduction half-equation: $MnO_4^-(aq) \rightarrow Mn^{2+}(aq)$

Unbalanced oxidation half-equation: $Li(s) \rightarrow Li^+(aq)$

These can be balanced using KOHES.

Balanced reduction half-equation:
$MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 4H_2O(l)$

Balanced oxidation half-equation: $Li(s) \rightarrow Li^+(aq) + e^-$

To be added together, the oxidation half-equation must be multiplied by 5 so that each half-equation contains 5 electrons, which will cancel each other out.

Balanced reduction half-equation:
$MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 4H_2O(l)$

Balanced oxidation half-equation: $5 \times (Li(s) \rightarrow Li^+(aq) + e^-)$

Therefore, the final balanced equation, where Li(s) has a coefficient of 5 is:

$MnO_4^-(aq) + 8H^+(aq) + 5Li(s) \rightarrow Mn^{2+}(aq) + 4H_2O(l) + 5Li^+(aq)$

Key science skills

15. a. [Potassium metal should be stored submerged in oil in a secure container[1]] [to prevent exposure to water and air (oxygen) in the environment.[2]]

✓ ✗ I have stated an appropriate way to store potassium metal.[1]

✓ ✗ I have justified my answer with reference to preventing exposure to water and air.[2]

b. [Potassium metal reacts explosively with water, which can cause burns on exposed skin.[1]] [A protective barrier could be put up around the container in which the reaction occurs, and tongs could be used to handle the potassium to avoid contact with skin.[2]] [Hydrogen gas is highly flammable.[3]] [The demonstration could be done under a fume hood to allow the gas to escape, away from any sparks or open flames.[4]] [There is a risk of the presence of broken glass if the explosion causes the container to break.[5]] [A strong plastic container should be used instead as it is less likely to shatter.[6]]

✓ ✗ I have identified a risk.[1]

✓ ✗ I have suggested a precaution to minimise this risk.[2]

✓ ✗ I have identified a second risk.[3]

✓ ✗ I have suggested a precaution to minimise this risk.[4]

✓ ✗ I have identified a third risk.[5]

✓ ✗ I have suggested a precaution to minimise this risk.[6]

c. i. [This oxidation half-equation contains the oxidising agent,[1]] [and electrons are present on the reactants side, indicating a reduction reaction.[2]]

✓ ✗ I have identified that this equation contains the oxidising agent.[1]

✓ ✗ I have identified that electrons are on the reactants side in this equation.[2]

ii. $K(s) \rightarrow K^+(aq) + e^-$

Alternative answer:

$K(s) + OH^-(aq) \rightarrow KOH(aq) + e^-$

FROM LESSONS 12B & 12D

Questions from multiple lessons

16. a. [Oxidation reaction: $Ni(s) \rightarrow Ni^{2+}(aq) + 2e^-$[1]] [Reduction reaction: $H_2SO_4(aq) + 2H^+(aq) + 2e^- \rightarrow SO_2(g) + 2H_2O(l)$[2]]

✓ ✗ I have written and labelled a balanced oxidation half-equation.[1]

✓ ✗ I have written and labelled a balanced reduction half-equation.[2]

b. $Ni(s) + H_2SO_4(aq) + 2H^+(aq) \rightarrow Ni^{2+}(aq) + SO_2(aq) + 2H_2O(l)$

c. [Yes,[1]][as there is a change in oxidation state of both sulfur (+6 to +4) and carbon (0 to +4), indicating a transfer of electrons.[2]]

- ✓ ✗ I have determined whether this is an example of a redox reaction.[1]
- ✓ ✗ I have justified my answer with reference to oxidation states.[2]

FROM LESSON 3A

17. a. [Oxidation: $C_6H_{12}O_6(aq) + 6H_2O(l) \rightarrow 24H^+(aq) + 24e^- + 6CO_2(g)$[1]][Reduction: $O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$[2]]

- ✓ ✗ I have written the correct oxidation half-equation.[1]
- ✓ ✗ I have written the correct reduction half-equation.[2]

b. i. [Cellular respiration is an exothermic reaction, whereas photosynthesis is endothermic.[1]][As these reactions are the reverse of each other, the endothermic reaction will have the greater activation energy. (This can be illustrated using energy profile diagrams).[2]][This means that it is less likely for the reactants of photosynthesis to have enough energy for the reaction to occur without an external energy input.[3]]

- ✓ ✗ I have identified whether each of these reactions are exothermic or endothermic.[1]
- ✓ ✗ I have explained that the endothermic reaction will have a greater activation energy.[2]
- ✓ ✗ I have explained that the reaction with greater activation energy is more likely to require an external energy input to occur.[3]

ii. The sun

FROM LESSONS 1C & 1D

3C Primary galvanic cells

Progress questions

1. C. The solutions in two half-cells in a galvanic cell are connected by a salt bridge. The electrodes are connected by a wire, and are only partially submerged in the electrolyte.

2. B. Positive ions from the salt bridge migrate towards the cathode, and negative ions from the salt bridge flow towards the anode.

3. D. In primary galvanic cells, reduction always occurs at the cathode and oxidation always occurs at the anode.

4. C. Electrons leave the site of oxidation (anode) and flow towards the site of reduction (cathode), i.e. from Q to S. Electrode S (of the reduction half-cell) is immersed in electrolyte R.

5. D. Calcium ions and aluminium metal will not undergo a redox reaction under SLC. $Ca^{2+}(aq)$ (strongest reducing agent present) is positioned below Al(s) (strongest oxidising agent present) in the electrochemical series, so this spontaneous reaction is not feasible.

6. A. Using the electrochemical series, the reduction reaction that occurs at the cathode involves the conversion of copper ions from the solution into solid copper, which will accumulate on the cathode. Therefore, an increase in mass should be measurable at the cathode.

7. B. The electrochemical series provides the half-equation for each reaction included (including the number of electrons transferred), as well as the conditions under which these reactions are feasible. However, the expected rate of reaction is not included.

8. D. The concentration of the Pb^{2+} ions in the solution is non-standard (not 1 M), so the electrochemical series cannot be used to reliably determine whether this reaction is feasible.

Deconstructed

9. C

10. D

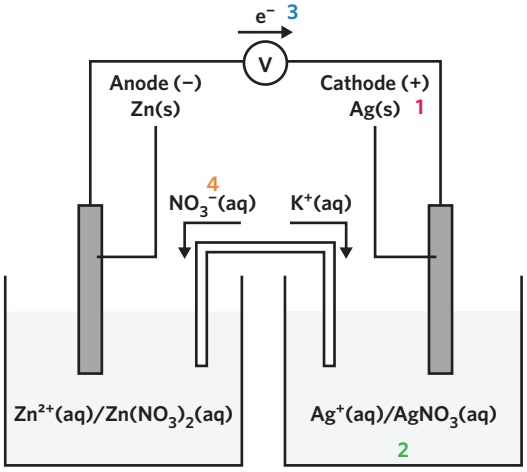
11. [The solution in Half-cell 1 will become darker green by the oxidation of Ni(s) according to the following half–equation: $Ni(s) \rightarrow 2e^- + Ni^{2+}(aq)$[1]][In order for this reaction to occur, the conjugate oxidising agent of metal X must be a stronger oxidising agent than Ni^{2+}.[2]][Out of the options given, only Pb^{2+} and Cu^{2+} are stronger oxidising agents than Ni^{2+}. Therefore, metal X could be either lead or copper.[3]]

- ✓ ✗ I have described the reaction that would cause the solution to turn a darker green.[1]
- ✓ ✗ I have determined that X cations must oxidise nickel.[2]
- ✓ ✗ I have identified the possible alternatives for metal X.[3]

Exam-style

12. C. For a reaction to occur, the strongest oxidising agent present (top left) must be positioned above the strongest reducing agent present (bottom right) in the electrochemical series. In beaker I, the strongest oxidising agent, $Ag^+(aq)$ is above the strongest reducing agent, Ni(s), and so a reaction is predicted. In beaker II, the strongest oxidising agent, $Cu^{2+}(aq)$, is below the strongest reducing agent, $I^-(aq)$, and so a reaction is not predicted to occur. In beaker III, the strongest oxidising agent, $Cl_2(g)$, is above the strongest reducing agent, $I^-(aq)$, and so a reaction is predicted to occur.

13.



- ✓ ✗ I have labelled each electrode, including their charges.[1]
- ✓ ✗ I have labelled the material of each electrode and the ionic solutions in each half-cell, including states.[2]
- ✓ ✗ I have shown the flow of electrons in the external circuit.[3]
- ✓ ✗ I have shown the flow of ions in an appropriate salt bridge.[4]

14. D. For a redox reaction to occur, the strongest oxidising agent present (top left) must be positioned above the strongest reducing agent present (bottom right) in the electrochemical series. This is only the case in the beakers containing Fe and Zn. Therefore, a reaction could only occur in these beakers.

15. B. Primary cell batteries are not 100% efficient and so will produce heat energy as well as electrical energy. Since the cell requires a flow of electrons from the site of oxidation to the site of reduction, Zn (the reducing agent) cannot be in direct contact with MnO_2 (the oxidising agent).

16. a. [Inès has not chosen an appropriate salt bridge.[1]][Instead of only migrating to each electrode, chloride anions from the salt bridge have reacted with silver cations to form an insoluble precipitate of AgCl.[2]]

- ✓ ✗ I have stated that Inès has not chosen an appropriate salt bridge.[1]
- ✓ ✗ I have explained that ions in the salt bridge have reacted with species in one half-cell.[2]

b. [The salt bridge is required to separate the half-cells and enable the flow of current.[1]][Without it, the circuit is incomplete and a current cannot flow.[2]]

- ✓ ✗ I have stated that the salt bridge separates the half-cells and allows a current to flow.[1]
- ✓ ✗ I have stated that without a salt bridge, the cell's circuit will be incomplete.[2]

c. [Potassium nitrate, KNO_3, would be an appropriate salt bridge.[1]] [It enables the flow of ions between half-cells[2]][and would not form a precipitate with any species in either half-cell.[3]]

- ✓ ✗ I have suggested an appropriate salt bridge.[1]
- ✓ ✗ I have provided one reason why this salt bridge would be appropriate.[2]
- ✓ ✗ I have provided a second reason why this salt bridge would be appropriate.[3]

Alternative answer:

Reason:

- does not contain a stronger oxidising agent or a stronger reducing agent.

17. [Emilia's prediction is not accurate.[1]]
[$Cu^{2+}(aq) + Fe(s) \rightarrow Cu(s) + Fe^{2+}(aq)$[2]]

- ✓ ✗ I have stated that Emilia's prediction is incorrect.[1]
- ✓ ✗ I have written the correct equation (including states) for the overall redox reaction.[2]

18. a. [Reduction: $H_2O_2(aq) + 2H^+(aq) + 2e^- \rightarrow H_2O_2(aq)$[1]]
[Oxidation: $H_2O_2(aq) \rightarrow 2e^- + 2H^+(aq) + O_2(g)$[2]]

- ✓ ✗ I have written the correct reduction half–equation.[1]
- ✓ ✗ I have written the correct oxidation half-equation.[2]

b. The rate of reaction is too slow or the activation energy is too high for the reaction to be observed.

Key science skills

19. a. [Bruno should complete a risk assessment to identify the dangers associated with the chemicals and materials involved in his experiment[1]][and to know how to design the experiment to best reduce this risk.[2]]

- ✓ ✗ I have stated that a risk assessment is important to identify the risks of an experiment.[1]
- ✓ ✗ I have stated that a risk assessment is important to understand how to reduce the risk of an experiment.[2]

b. [Bruno has forgotten to include potential chemicals produced (products) in his experiment.[1]][These are also often hazardous, so they must be included in the risk assessment.[2]]

- ✓ ✗ I have identified the missing component of this risk assessment.[1]
- ✓ ✗ I have explained why this component is a necessary part of a risk assessment.[2]

c. Bruno should run water down the sink to dilute the zinc nitrate.

d. [Bruno should remove these rods from their respective solutions and clean them thoroughly instead of disposing them with chemical waste[1]][so that they can be reused in future experiments.[2]]

- ✓ ✗ I have suggested how Bruno can implement green chemistry principles in his experiment.[1]
- ✓ ✗ I have explained my suggestion.[2]

FROM LESSON 12B

Questions from multiple lessons

20. A. Based on the electrochemical series, $H^+(aq)$ is a stronger oxidising agent than Fe^{2+}, and Fe(s) is a stronger reducing agent than $H_2(g)$.

21. a. $n(Zn) = \frac{m}{M}$

$n(Zn) = \frac{1.403\ g}{65.4\ g\ mol^{-1}}$ (1 MARK)

$n(Zn) = 0.02145\ mol$ (1 MARK)

b. $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

c. $n(\text{Cu}) = n(\text{Zn})$

$n(\text{Cu}) = 0.02145 \text{ mol}$ (1 MARK)

$m(\text{Cu}) = n \times M$

$m(\text{Cu}) = (2.145 \times 10^{-2} \text{ mol}) \times 63.5 \text{ g mol}^{-1}$ (1 MARK)

$m(\text{Cu}) = 1.36 \text{ g}$ (1 MARK)

FROM LESSON 2A

3D Designing galvanic cells

Progress questions

1. C. Platinum is inert and conductive, so will enable the flow of electrons through the external circuit, and will not react with species in the half-cell over time.

2. D. H_2 gas is bubbled in at a non-standard pressure and the temperature is not known. Additionally, the solutions in each half-cell are at non-standard concentrations. Therefore, the electrochemical series cannot be reliably used to predict half-cell reactions in this galvanic cell.

3. A. Standard conditions for a standard half-cell require a temperature of 298 K (or 25 °C), a pressure of 100 kPa, and ions in a solution to have concentration 1.0 M.

4. D. The potential difference between the electrodes of each cell can be calculated by subtracting the E^0 values for each half-cell, found in the electrochemical series.

Cell I: $E_{\text{cell}} = +1.09 \text{ V} - (+0.34 \text{ V})$

$E_{\text{cell}} = +0.75 \text{ V}$

Cell II: $E_{\text{cell}} = -0.14 \text{ V} - (-0.76 \text{ V})$

$E_{\text{cell}} = +0.62 \text{ V}$

Cell III: $E_{\text{cell}} = +1.09 \text{ V} - (+0.54 \text{ V})$

$E_{\text{cell}} = +0.55 \text{ V}$

Cell IV: $E_{\text{cell}} = +0.77 \text{ V} - (-0.28 \text{ V})$

$E_{\text{cell}} = +1.05 \text{ V}$

5. A. When a galvanic cell is created with Fe^{3+}/Fe^{2+} and Sn^{4+}/Sn^{2+} half-cells:

$E_{\text{cell}} = E^0(Fe^{3+}/Fe^{2+} \text{ half-cell}) - E^0(Sn^{4+}/Sn^{2+} \text{ half-cell})$

$E_{\text{cell}} = +0.77 \text{ V} - (+0.15 \text{ V})$

$E_{\text{cell}} = +0.62 \text{ V}$

6. C. According to the information from the electrochemical series

$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$ $\quad E^0 = +1.36 \text{ V}$

$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}$ $\quad E^0 = +0.77 \text{ V}$

$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$ $\quad E^0 = +0.54 \text{ V}$

Based on the information supplied in the question, ClO_2/ClO_2^- is located above Fe^{3+}/Fe^{2+}, but below Cl_2/Cl^-, i.e. the order of the redox pairs in terms of decreasing oxidising agent strength/increasing reducing agent strength is:

- $Cl_2(g)/Cl^-(aq)$
- $ClO_2(g)/ClO_2^-(aq)$
- $Fe^{3+}(aq)/Fe^{2+}(aq)$
- $I_2(s)/I^-(aq)$

Therefore, $Fe^{2+}(aq)$ will be oxidised by $Cl_2(g)$ and $ClO_2(g)$, but not by $I_2(s)$.

Deconstructed

7. B **8.** B

9. $E_{\text{cell}} = E^0(\text{reduction half-cell}) - E^0(\text{oxidation half-cell})$

$E_{\text{cell}} = E^0(\text{Equation 2}) - E^0(\text{Equation 1})$

$E^0(\text{Equation 2}) = E_{\text{cell}} + E^0(\text{Equation 1})$

$E^0(\text{Equation 2}) = +1.50 \text{ V} + (-0.76 \text{ V})$

$E^0(\text{Equation 2}) = +0.74 \text{ V}$

Exam-style

10. B. According to the electrochemical series, Ag is the strongest oxidising agent present (top left). This will form the cathode where reduction always occurs (RedCat).

The predicted voltage, under standard conditions is $E_{\text{cell}} = E^0$(half-cell where reduction takes place: most positive value) $- E^0$(half-cell where oxidation takes place: least positive value)

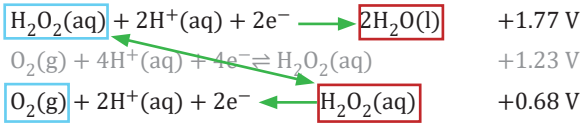
$E_{\text{cell}} = +0.80 \text{ V} - (-0.76 \text{ V})$

$E_{\text{cell}} = +1.56 \text{ V}$

11. A.

Option	Half-reactions	Cell voltage
A	$Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$ $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$	$-0.25 \text{ V} - (-0.76 \text{ V}) = +0.51 \text{ V}$
B	$2H^+(aq) + 2e^- \rightarrow H_2(g)$ $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$	$0.00 \text{ V} - (-0.44 \text{ V}) = +0.44 \text{ V}$
C	$Ag^+(aq) + e^- \rightarrow Ag(s)$ $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$	$+0.80 \text{ V} - (+0.34 \text{ V}) = +0.46 \text{ V}$
D	No reaction occurs, as one half-cell only contains an inert electrode and pure water.	No voltage produced.

12. D. According to the electrochemical series, $H_2O_2(aq)$ can act as both an oxidising agent and a reducing agent. The possible redox half-reactions of the species present according to the electrochemical series are:



Based on this ranking, the following half-cell reactions will occur.

Strongest oxidising agent (top left) and strongest reducing agent (bottom right)

Reduction: $H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$

Oxidation: $O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$

Therefore, the maximum cell voltage is:

$E_{\text{cell}} = +1.77 \text{ V} - (+0.68 \text{ V})$

$E_{\text{cell}} = +1.09 \text{ V}$

According to this information, standard half-cell reactions are feasible with an expected voltage of +1.09 V produced between the anode and cathode. Therefore, the most likely explanation for no reaction being observed is a very slow reaction rate due to a very high activation energy.

13. C. In galvanic cells, electrons flow from the (−) electrode to the (+) electrode. Since electrons always move from the site of oxidation to the site of reduction, the stronger oxidising agent – the species that is reduced – must be in the half-cell containing the (+) electrode. In the galvanic cell on the left, $Ag(NH_3)_2^+(aq)$ is the strongest oxidising agent – stronger than $Ag(CN)_2^-(aq)$.

In the galvanic cell on the right, $Ag^+(aq)$ is the stronger oxidising agent – stronger than $Ag(NH_3)_2^+(aq)$.

Therefore, the correct order of the reduction half-equations in order of decreasing (highest to lowest) electrode potentials is

$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$ $\quad E^0_2$

$Ag(NH_3)_2^+(aq) + e^- \rightleftharpoons Ag(s) + 2NH_3(aq)$ $\quad E^0_1$

$Ag(CN)_2^-(aq) + e^- \rightleftharpoons Ag(s) + 2CN^-(aq)$ $\quad E^0_3$

14. a.

Half-equation	E^0
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34 V
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	
$Cr^{3+}(aq) + 3e^- \rightleftharpoons Cr(s)$	

b. Both E^0 values are below the H^+/H_2 half-cell, but there is not enough information to identify their relative positions.

Alternative answers:

- Both of the other half-equations have negative E^0 values (positioned below the standard hydrogen half-cell in the electrochemical series). However, to determine their locations, the potential difference of each when connected to the standard hydrogen electrode would need to be recorded.
- Both are oxidised by H^+, but there is not enough information to determine which has the stronger reducing agent.
- The data indicates that electrons flow from the two other half-cells to the SHE, but does not give the potential differences.

c. $H^+(aq)$ was consumed, so $[H^+(aq)]$ decreased, and hence pH increased.

15. a. The electrochemical series is only an accurate predictor for redox reactions when they occur at standard conditions (1.0 M concentrations, 100 kPa and 298 K or 25 °C). Since the temperature is above 25 °C, the electrochemical series cannot be reliably used.

b. [The standard electrode potential values in the electrochemical series are only valid when solutions in the relevant half-cell have concentrations of 1.0 M.[1]][Since the concentrations of the solution may be decreasing or increasing as ions in the solution are either produced or consumed during oxidation or reduction half-reactions, the voltage will be subject to change as concentrations change throughout the experiment.[2]]

✓ ✗ I have identified the importance of 1.0 M concentrations in determining standard electrode potentials.[1]

✓ ✗ I have linked my answer to the question.[2]

Key science skills

16. a. [Concentration of solutions[1]][and temperature need to be controlled.[2]]

✓ ✗ I have identified a first factor that needs to be controlled.[1]

✓ ✗ I have identified a second factor that needs to be controlled.[2]

b. $[MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightleftharpoons Mn^{2+}(aq) + 4H_2O(l)]^1$
$[Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)]^2$
$[Ag^+(aq) + e^- \rightleftharpoons Ag(s)]^3$
$[Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)]^4$
$[Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)]^5$
$[Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)]^6$

✓ ✗ I have correctly balanced two half-equations.[1]

✓ ✗ I have correctly balanced two more half-equations.[2]

✓ ✗ I have correctly balanced two more half-equations.[3]

✓ ✗ I have arranged each reaction in the correct order.[4]

✓ ✗ I have included correct states for all species.[5]

✓ ✗ I have used the correct (bidirectional) arrow.[6]

c. [Pierre should complete multiple trials for each half-cell combination and calculate the average voltage between these.[1]][This reduces the impact of random error.[2]]

✓ ✗ I have suggested how Pierre could increase the validity of their results.[1]

✓ ✗ I have explained my answer.[2]

d. Sodium metal is a very strong reducing agent that would react explosively (and dangerously) with water in the Na^+ solution.

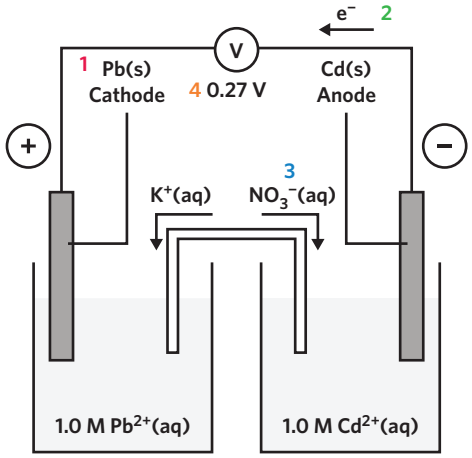
FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

17. a. $Cd(s) \rightarrow Cd^{2+}(aq) + 2e^-$

b. $Cd(s) + Pb^{2+}(aq) \rightarrow Cd^{2+}(aq) + Pb(s)$

c.



- ✓ ✗ I have labelled the anode and cathode, including their charges and materials.[1]
- ✓ ✗ I have labelled the direction of electron flow.[2]
- ✓ ✗ I have labelled the flow of ions through the salt bridge.[3]
- ✓ ✗ I have calculated and labelled the voltage produced by this cell.[4]

FROM LESSONS 3B & 3C

18. a. No water is present because lithium would react explosively with water, as lithium is a very strong reducing agent.

b. Lithium is a common choice because it is a very good reducing agent, and therefore when it is combined with iodine, a large voltage is produced.

FROM LESSON 3B & 3C

19. a. [$Br^-(aq)$ would be preferentially oxidised to form $Br_2(l)$ rather than forming $HOBr(aq)$,[1] as the half-reaction $Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$ has the least positive E^0 value out of the relevant half-reactions.[2]]

- ✓ ✗ I have identified that $Br_2(l)$ is predicted to be produced instead of $HOBr(aq)$.[1]
- ✓ ✗ I have justified my answer using E^0 values.[2]

b. $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$

FROM LESSONS 3B & 3C

3E Fuel cells

Progress questions

1. B. Fuel cells are a type of galvanic cell, so their anode is negative. Reduction always occurs at the cathode. Electrons travel through the external circuit; ions travel across the electrolyte.

2. D. Fuel cells are non-rechargeable galvanic cells (hence their electrodes are separated and they convert chemical energy to electrical energy) whose reactants are continually supplied from an external source.

3. A. Fuel cells are primary galvanic cells and hence do not require an external power source. In a fuel cell, the fuel is oxidised at the anode, and so the fuel must come into contact with the anode.

4. C. Fuel cell electrodes are unreactive and generally expensive due to their porosity (and due to catalyst impregnation). Hydrogen and oxygen do not react directly in a fuel cell; they react indirectly to produce electrical energy. Porous electrodes have a greater surface area than solid electrodes, allowing greater passage of charges and reactants.

5. B. Fuel cells are expensive to manufacture, but cheap to maintain.

Deconstructed

6. C **7.** B

8. A. $E_{cell} = E^0(\text{reduction}) - E^0(\text{oxidation})$

$E_{cell} = +1.23\ V - (+0.06\ V)$

$E_{cell} = +1.17\ V$

Exam-style

9. a. $H_2O(g)$

b. $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(g)$

c. i. No CO_2 or sulfur- and nitrogen-containing compounds are produced by this fuel cell.

Alternative answer:

- The fuel cell is likely much more efficient than a petrol engine.

ii. The fuel is much more expensive to produce than a petrol engine.

Alternative answers:

- Hydrogen gas requires electricity to produce and is difficult to store.
- Hydrogen gas presents a risk of reacting explosively.

d. i. Porous electrodes maximise the efficiency of diffusion of reactant gases to the electrolyte.

Alternative answer:

- Porous electrodes have increased surface area, enhancing the ability of catalysts to increase reaction rate.

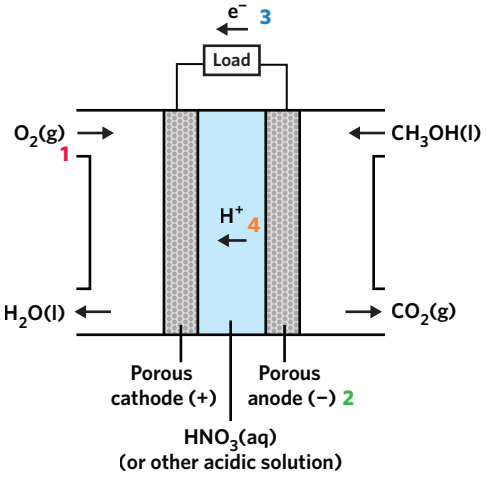
ii. Porous electrodes are expensive to manufacture.

10. a. $2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$

Alternative answer:

- $CH_3OH(l) + \frac{3}{2}O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

b.



- ✓ ✗ I have written all species entering and exiting the cell.[1]
- ✓ ✗ I have drawn and labelled a porous anode and cathode.[2]
- ✓ ✗ I have correctly identified electrode polarities and direction of electron flow.[3]
- ✓ ✗ I have labelled the electrolyte and the direction of H^+ flow.[4]

c. $E_{cell} = E^0(\text{reduction}) - E^0(\text{oxidation})$

$E_{cell} = +1.23\ \text{V} - (-0.39\ \text{V})$

$E_{cell} = +1.62\ \text{V}$

d. At 200 °C, both methanol and the electrolyte would have vaporised, preventing the cell from functioning as designed.

11. A. All fuel cells produce heat as a by-product. O_2 is reduced to form CO_3^{2-}. Since fuel cells release energy, the enthalpy of the reactants is greater than the enthalpy of the products. CO_2 is absorbed from the environment by this fuel cell.

12. D. The positive electrode is the cathode, where, according to the diagram, O_2 and CO_2 react to form CO_3^{2-}, producing the unbalanced half-equation $O_2 + CO_2 \rightarrow CO_3^{2-}$.

Key science skills

13. a. i. The electrolyte completes the circuit by allowing the flow of charged particles (ions) through the cell.

ii. $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

iii. [It is necessary to control any possible ignition sources (e.g. sparks or open flames) to minimise the risk of explosion.[1]][Hydrogen containers should also be selected carefully and regularly maintained to ensure they can withstand the high pressures necessary for storage.[2]]

✓ ✗ I have identified a first safety measure that should be taken.[1]

✓ ✗ I have identified a second safety measure that should be taken.[2]

Alternative answers:

- Using hydrogen release detectors could allow a leak to be identified and managed early.
- It is essential to follow appropriate hazardous materials guidelines for hydrogen gas.

b. i. [A PEM fuel cell produces no toxic or environmentally hazardous products, only water.[1]][A PEM fuel cell generates less noise than a diesel engine.[2]]

✓ ✗ I have identified a first advantage of using a PEM fuel cell.[1]

✓ ✗ I have identified a second advantage of using a PEM fuel cell.[2]

Alternative answers:

- The fuel cell is likely to be much more energy efficient than a diesel engine.
- Hydrogen gas is very energy-dense, meaning less fuel needs to be carried underwater.
- The PEM fuel cell generates less excess heat than a diesel engine, mitigating the need for cooling.
- The water produced by the PEM fuel cell could be used on the submarine

ii. [Since the submarine also has a diesel engine, energy from this engine could be used[1]][to electrolyse seawater from the ocean surface and hence produce hydrogen gas.[2]]

✓ ✗ I have identified a source of energy for electrolysis.[1]

✓ ✗ I have identified electrolysis of seawater as a source of hydrogen gas.[2]

Alternative answer:

- When the submarine is at the surface, the submarine could use solar energy via solar panels to electrolyse seawater and hence produce hydrogen gas.

FROM LESSONS 12A & 12B

Questions from multiple lessons

14. B. Statement 1: Since the overall reaction produces energy for fuel cells and other galvanic cells, it is exothermic.

Statement 2: Electrons are 'consumed' during reduction at the cathode, which is positive for fuel cells and other galvanic cells.

Statement 3: In fuel cells, oxidising and reducing agents are supplied externally, rather than stored in each half-cell like in other galvanic cells.

Statement 4: In fuel cells and other galvanic cells, the electrodes must remain in contact with the reactants and the electrolyte for the reaction to occur.

Statement 5: The electrodes are not consumed in fuel cells, and so they do not need to be replaced regularly in fuel cells, unlike in other galvanic cells.

FROM LESSON 3C

15. a. CH_4

b. Electrode I: Positive (+), Electrode II: Negative (−)

c. $CH_4(g) + 2H_2O(l) \rightarrow CO_2(g) + 8H^+ + 8e^-$

d. [$CH_4(g) + 2O_2(g)$[1]][$\rightarrow CO_2(g) + 2H_2O(l)$[2]]

✓ ✗ I have correctly balanced the reactants and identified their states.[1]

✓ ✗ I have correctly balanced the products and identified their states.[2]

e. $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

f. [If the electrodes were not porous, the gaseous reactants would not be able to diffuse through them and come into contact with the electrolyte.[1]][As a result, the desired reaction would not occur, and no electrical energy would be generated.[2]]

✓ ✗ I have explained the effect of this change on diffusion.[1]

✓ ✗ I have explained the consequent effect on electricity output.[2]

g. $m(CH_4) = 1.00 \times 10^3\ \text{g}$

$n(CH_4) = \frac{m}{M}$

$n(CH_4) = \frac{1.00 \times 10^3\ \text{g}}{16.0\ \text{g mol}^{-1}}$

$n(CH_4) = 62.5\ \text{mol}$ (1 MARK)

This cell must operate at temperatures below 100 °C, so CO_2 is the only greenhouse gas produced (liquid water is produced instead of water vapour). Hence,

$n(\text{greenhouse gas produced}) = n(CO_2)$ (1 MARK)

From the equation,

$n(CO_2) : n(CH_4)$

1 : 1

$n(CO_2) = n(CH_4)$

$n(CO_2) = 62.5 \text{ mol}$

$m(CO_2) = n \times M$

$m(CO_2) = 62.5 \text{ mol} \times 44.0 \text{ g mol}^{-1}$

$m(CO_2) = 2750 \text{ g}$

$m(CO_2) = 2.75 \text{ kg}$ (1 MARK)

h. [This fuel cell converts methane gas, an extremely potent greenhouse gas, to carbon dioxide, a less potent greenhouse gas, resulting in a net 'reduction' in contribution to the enhanced greenhouse effect.[1]][Biogas is a biofuel, meaning it is obtained from renewable plant matter rather than from drilling or fracking, minimising environmental disruption.[2]]

✓ ✗ I have explained a first environmental advantage of this fuel cell.[1]

✓ ✗ I have explained a second environmental advantage of this fuel cell.[2]

Alternative answer:

- This fuel cell is likely more energy efficient than producing energy via direct combustion of biogas, resulting in less CO_2 produced per amount of useful energy generated.

FROM LESSONS 1B & 2A

3F Faraday's Laws in galvanic and fuel cells

Progress questions

1. D. Faraday's First Law states that anode mass loss is directly proportional to charge carried. When the mass loss of the anode is tripled, the charge carried is tripled.

$Q = 3 \times (3.8 \times 10^4 \text{ C})$

$Q = 1.1 \times 10^5 \text{ C}$ (2 sig. figs)

2. C. $Q = It$

$Q = 0.50 \text{ A} \times 180 \text{ s}$

$Q = 90 \text{ C}$

3. C. Option A: $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$.
$n(e^-) = 3 \times 1 \text{ mol} \Rightarrow 3 \text{ mol}$

Option B: $Co(s) \rightarrow Co^{2+}(aq) + 2e^-$.
$n(e^-) = 2 \times 1 \text{ mol} \Rightarrow 2 \text{ mol}$

Option C: $Ni(s) \rightarrow Ni^{2+}(aq) + 2e^-$.
$n(e^-) = 2 \times 2 \text{ mol} \Rightarrow 4 \text{ mol}$

Option D: $Ag(s) \rightarrow Ag^{3+}(aq) + 3e^-$.
$n(e^-) = 1 \times 3 \text{ mol} \Rightarrow 3 \text{ mol}$

4. A. $n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{6.85 \times 10^4 \text{ C}}{96\,500 \text{ C mol}^{-1}}$

$n(e^-) = 0.710 \text{ mol}$

5. B. From the oxidation half-equation,

$n(H_2) : n(e^-)$

1 : 2

$n(H_2) = \frac{1}{2} \times 3.00 \text{ mol}$

$n(H_2) = 1.50 \text{ mol}$

$V(H_2) = n(H_2) \times V_m$

$V(H_2) = 1.50 \text{ mol} \times 24.8 \text{ L mol}^{-1}$

$V(H_2) = 37.2 \text{ L}$

6. B. The overall equation is $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$

From Question 5,

$n(H_2) = 1.50 \text{ mol}$

$n(H_2) : n(H_2O)$

1 : 1

$n(H_2O) = 1.50 \text{ mol}$

$m(H_2O) = n(H_2O) \times M(H_2O)$

$m(H_2O) = 1.50 \text{ mol} \times 18.0 \text{ g mol}^{-1}$

$m(H_2O) = 27.0 \text{ g}$

7. B. $Q = It$

$t = \frac{Q}{I}$

$t = \frac{7200 \text{ C}}{0.330 \text{ A}}$

$t = 2.18 \times 10^4 \text{ s}$ (3 sig. figs)

Deconstructed

8. B **9.** B

10. For 100% efficiency:

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{5.00 \times 10^6 \text{ C}}{96\,500 \text{ C mol}^{-1}}$

$n(e^-) = 51.813 \text{ mol}$ (1 MARK)

$n(CH_4) : n(e^-)$

1 : 8

$n(CH_4) = \frac{1}{8} \times 51.813 \text{ mol}$

$n(CH_4) = 6.4767 \text{ mol}$

$V(CH_4) = n \times V_m$

$V(CH_4) = 6.4767 \text{ mol} \times 24.8 \text{ L mol}^{-1}$

$V(CH_4) = 160.62 \text{ L}$ (1 MARK)

For 60% efficiency:

$V(CH_4) = \frac{1}{0.60} \times 160.62 \text{ L}$

$V(CH_4) = 268 \text{ L}$ (3 sig. figs) (1 MARK)

Exam-style

11. a. $Q = It$

$Q = 2.3\ \text{A} \times 180\ \text{s}$

$Q = 414\ \text{C}$

b. $n(\text{e}^-) = \frac{Q}{F}$

$n(\text{e}^-) = \frac{414\ \text{C}}{96\,500\ \text{C mol}^{-1}}$

$n(\text{e}^-) = 0.00429\ \text{mol}$

c. [The balanced oxidation half-equation for a copper anode is $\text{Cu} \rightarrow \text{Cu}^{2+} + 2\text{e}^-$, whereas the balanced oxidation half-equation for a silver anode is $\text{Ag} \rightarrow \text{Ag}^+ + \text{e}^-$.[1]][Faraday's Second Law states that the number of moles of electrons produced is directly proportional to the coefficient of electrons in the balanced oxidation half-equation.[2]][As a result, using a silver anode instead of a copper anode would result in $\frac{1}{2}$ the amount of electrons produced.[3]]

✓ ✗ I have given the relevant balanced oxidation half-equations.[1]

✓ ✗ I have stated Faraday's Second Law.[2]

✓ ✗ I have applied Faraday's Second Law to the relevant half-equations.[3]

12. C. If electrolyte is acidic, oxidation half-equation is:
$\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$

If electrolyte is alkaline, oxidation half-equation is:
$\text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2\text{e}^-$

In both cases,

$n(\text{e}^-) = 2 \times n(\text{H}_2)$

$n(\text{e}^-) = 2 \times (1.00 \times 10^{-5}\ \text{mol})$

$n(\text{e}^-) = 2.00 \times 10^{-5}\ \text{mol}$

$Q = n(\text{e}^-) \times F$

$Q = (2.00 \times 10^{-5}\ \text{mol}) \times 96\,500\ \text{C mol}^{-1}$

$Q = 1.93\ \text{C}$

$I = \frac{Q}{t}$

$I = \frac{1.93\ \text{C}}{1\ \text{s}}$

$I = 1.93\ \text{A}$

13. A. $n(\text{e}^-) = \frac{Q}{F}$

$n(\text{e}^-) = \frac{1.00\ \text{C}}{96\,500\ \text{C mol}^{-1}}$

$n(\text{e}^-) = 1.036 \times 10^{-5}\ \text{mol}$

$N(\text{e}^-) = n \times N_\text{A}$

$N(\text{e}^-) = (1.036 \times 10^{-5}\ \text{mol}) \times (6.02 \times 10^{23}\ \text{mol}^{-1})$

$N(\text{e}^-) = 6.24 \times 10^{18}$ (3 sig. figs)

14. a. $\text{CH}_3\text{CH}_2\text{OH} + 3\text{H}_2\text{O} \rightarrow 2\text{CO}_2 + 12\text{H}^+ + 12\text{e}^-$

b. From the equation,

$n(\text{e}^-) : n(\text{CH}_3\text{CH}_2\text{OH})$

12 : 1

$n(\text{e}^-) = 12 \times n(\text{CH}_3\text{CH}_2\text{OH})$

$n(\text{e}^-) = 12 \times 0.100\ \text{mol}$

$n(\text{e}^-) = 1.20\ \text{mol}$ (1 MARK)

At 100% efficiency:

$Q = n(\text{e}^-) \times F$

$Q = 1.20\ \text{mol} \times 96\,500\ \text{C mol}^{-1}$

$Q = 1.158 \times 10^5\ \text{C}$ (1 MARK)

$t = \frac{Q}{I}$

$t = \frac{1.158 \times 10^5\ \text{C}}{1.04\ \text{A}}$

$t = 1.113 \times 10^5\ \text{s}$

$t = \frac{1.113 \times 10^5}{60 \times 60}$ hours

$t = 30.929$ hours (1 MARK)

At 30% efficiency:

$t = \frac{30}{100} \times 30.929$ hours

$t = 9.3$ hours (1 MARK)

Key science skills

15. a. [Connect the cell for a measured length of time, and measure the average current produced during this time.[1]][Calculate the charge carried by the cell during this time using $Q = It$.[2]][Measure the initial and final mass of the anode/cathode and hence find the number of moles of anode consumed/cathode produced using the formula $n = \frac{m}{M}$.[3]][Use this value and a balanced half-equation to calculate $n(\text{e}^-)$.[4]][Use the formula $F = \frac{Q}{n(\text{e}^-)}$ to determine a value for the Faraday constant, F.[5]]

✓ ✗ I have suggested that current and time be measured.[1]

✓ ✗ I have suggested that charge be calculated using an appropriate formula.[2]

✓ ✗ I have suggested that the change in amount of anode/cathode be determined.[3]

✓ ✗ I have suggested that $n(\text{e}^-)$ be calculated.[4]

✓ ✗ I have suggested the appropriate formula to calculate the Faraday constant.[5]

b. [Some mass may drop off from the anode/cathode, affecting the mass change determined.[1]][The efficiency of electricity production by the galvanic cell is unlikely to be 100%.[2]]

✓ ✗ I have given a first possible reason for any disparity.[1]

✓ ✗ I have given a second possible reason for any disparity.[2]

Alternative answers:

- If the anode/cathode is not properly dried before weighing, the measured mass change may be inaccurate.
- If the current varies significantly over the course of the experiment, the calculated average current may be inaccurate.
- Impurities on the anode/cathode will introduce errors into the calculations.

FROM LESSONS 12B & 12D

Questions from multiple lessons

16. a. i. [Cathode: $Ag^+(aq) + e^- \rightarrow Ag(s)$[1]]
[Anode: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$[2]]

I have correctly written the half-equation occurring at the cathode.[1]

I have correctly written the half-equation occurring at the anode.[2]

ii. $E_{cell} = E^0$(most positive value: oxidising agent half-cell) $- E^0$(least positive value: reducing agent half-cell)

$E_{cell} = +0.80\text{ V} - (-2.37\text{ V})$

$E_{cell} = +3.17\text{ V}$

b. i. $m(\text{Mg lost}) = m(\text{Mg initial}) - m(\text{Mg final})$

$m(\text{Mg lost}) = 0.440\text{ g} - 0.340\text{ g}$

$m(\text{Mg lost}) = 0.100\text{ g}$

$n(\text{Mg}) = \frac{m}{M}$

$n(\text{Mg}) = \frac{0.100\text{ g}}{24.3\text{ g mol}^{-1}}$

$n(\text{Mg}) = 0.0041152\text{ mol}$ (1 MARK)

$n(e^-) : n(\text{Mg})$

2 : 1

$n(e^-) = \frac{2}{1} \times n(\text{Mg})$

$n(e^-) = \frac{2}{1} \times 0.00411523\text{ mol}$

$n(e^-) = 0.00823045\text{ mol}$ (1 MARK)

$Q = n(e^-) \times F$

$Q = 0.00823045\text{ mol} \times 96\,500\text{ C mol}^{-1}$

$Q = 794.239\text{ C}$ (1 MARK)

ii. $I = \frac{Q}{t}$

$I = \frac{794.239\text{ C}}{300\text{ s}}$

$I = 2.64746\text{ A}$

c. i. $q = VIt$

$q = 3.17\text{ V} \times 2.64746\text{ A} \times 300\text{ s}$

$q = 2517.74\text{ J}$

ii. $q = mc\Delta T$

$\Delta T = \frac{q}{mc}$

$\Delta T = \frac{2517.74\text{ J}}{50.0\text{ g} \times 4.18\text{ J g}^{-1}\,^\circ\text{C}^{-1}}$

$\Delta T = 12.0\,^\circ\text{C}$ (3 sig. figs)

FROM LESSONS 2B, 3B & 3D

17. a. $m(\text{octane}) = 1.65 \times 10^3\text{ g}$

$q_{theoretical} = m(\text{octane}) \times \text{heat of combustion of octane}$

$q_{theoretical} = (1.65 \times 10^3)\text{ g} \times 47.9\text{ kJ g}^{-1}$

$q_{theoretical} = 7.9035 \times 10^4\text{ kJ}$ (1 MARK)

$q_{actual} = 27.7 \times 10^3\text{ kJ}$

$\%\text{ efficiency} = \frac{\text{actual value}}{\text{theoretical value}} \times 100\%$

$\%\text{ efficiency} = \frac{27.7 \times 10^3\text{ kJ}}{7.9035 \times 10^4\text{ kJ}} \times 100\%$

$\%\text{ efficiency} = 35.0\%$ (1 MARK)

b. $n(H_2) = \frac{V}{V_m}$

$n(H_2) = \frac{2.03\text{ L}}{24.8\text{ L mol}^{-1}}$

$n(H_2) = 0.0818548\text{ mol}$ (1 MARK)

$n(e^-) : n(H_2)$

2 : 1

$n(e^-) = 2 \times n(H_2)$

$n(e^-) = 2 \times 0.0818548\text{ mol}$

$n(e^-) = 0.163710\text{ mol}$ (1 MARK)

$Q_{theoretical} = n(e^-) \times F$

$Q_{theoretical} = 0.163710\text{ mol} \times 96\,500\text{ C mol}^{-1}$

$Q_{theoretical} = 1.57980 \times 10^4\text{ C}$ (1 MARK)

$Q_{actual} = 9.50 \times 10^3\text{ C}$

$\%\text{ efficiency} = \frac{\text{actual value}}{\text{theoretical value}} \times 100\%$

$\%\text{ efficiency} = \frac{9.50 \times 10^3\text{ C}}{1.57980 \times 10^4\text{ C}} \times 100\%$

$\%\text{ efficiency} = 60.1\%$ (1 MARK)

c. i. Fuel cells are more efficient, so the vehicle needs to carry less fuel.

Alternative answer:

- Fuel cells produce less harmful emissions than internal combustion engines.

ii. Infrastructure for fuel cell vehicles (e.g. hydrogen refuelling stations) is currently limited.

Alternative answer:

- Fuel cells are expensive to build, increasing vehicle cost.

FROM LESSONS 2A, 2C & 3E

3G Fuel cell challenges and innovations

Progress questions

1. A. Although burning plastic reduces landfill, it releases harmful chemicals into the atmosphere, contravening green chemistry principles.

2. D. Recycling materials minimises resource consumption without impacting production, hence it helps achieve Goal 12: Responsible consumption and production.

3. C. Although polymer membranes are generally more expensive than aqueous solutions and are rarely renewable, they tend to increase current efficiency and can generally function at both low and high temperatures.

4. B. Using the thermal energy produced from fuel cells for heating (cogeneration) decreases energy 'loss', whereas producing superfluous energy, slowing reaction rate, and removing the catalyst all decrease overall efficiency.

5. C. Platinum is a mineral, and is hence non-renewable. Wastewater, carbon dioxide, and the plants used to produce bioethanol can all be replenished by natural processes in a short period of time.

6. D. Sustainability relates to relative rates of consumption and production, but also must factor in the difficulty of this replenishment: a resource that is renewable in theory is not necessarily sustainable in practice.

Deconstructed

7. B

8. A

9. [To reduce costs, fuel cell engines using cheaper, carbon-based catalysts such as graphene, or even enzymes, could be developed.[1]] [To avoid issues with hydrogen fuel storage, alternative fuels, such as biofuels, could be used in fuel cell vehicle engines instead of hydrogen fuel.[2]]

- ✓ ✗ I have suggested a first fuel cell vehicle innovation to combat current challenges.[1]
- ✓ ✗ I have suggested a second fuel cell innovation to combat current challenges.[2]

Exam-style

10. [The ski lodge could consider the use of a membrane electrolyte,[1]] [since membranes likely perform better than aqueous electrolytes (due to water freezing) in the subzero temperatures of a ski lodge.[2]] [The ski lodge could also make use of cogeneration or 'combined heat and power' to improve efficiency,[3]] [since the 'waste' heat produced by the fuel cell could be used for heating the lodge.[4]]

- ✓ ✗ I have given a first fuel cell efficiency consideration or innovation.[1]
- ✓ ✗ I have explained why this is appropriate for a ski lodge.[2]
- ✓ ✗ I have given a second fuel cell efficiency consideration or innovation.[3]
- ✓ ✗ I have explained why this is appropriate for a ski lodge.[4]

11. a. [The fuel cell produces no carbon dioxide or other harmful emissions and costs only $100,[1]] [meaning it helps achieve Sustainable Development Goal 7: Affordable and clean energy.[2]]

- ✓ ✗ I have identified one aspect of the PEM fuel cell that aligns with green chemistry principles.[1]
- ✓ ✗ I have linked this aspect to a Sustainable Development Goal.[2]

b. [The electrolyte membrane has a short lifespan of 1 year, which would ideally be improved to minimise waste.[1]] [This would align with Sustainable Development Goal 12: Responsible consumption and production.[2]]

- ✓ ✗ I have identified one improvement for the PEM fuel cell that aligns with green chemistry principles.[1]
- ✓ ✗ I have linked this improvement to a Sustainable Development Goal.[2]

12. a. i. As enzymes can only catalyse the desired reaction and not any side reactions, the impact of these side reactions on fuel cell efficiency is minimised.

ii. Enzymes are much cheaper and more widely available than precious metal catalysts.

b. [Renewable feedstocks are substances consumed by fuel cells that can be replenished in a short period of time, particularly biomass.[1]] [The sustainability of feedstocks depends on their relative rates of consumption and production; if production can match demand, the feedstock is sustainable, such as in the case of human waste or algae.[2]] [Conversely, fuels cultivated by replacing existing food crops are likely to be unsustainable, considering society's massive energy demand.[3]]

- ✓ ✗ I have defined renewable feedstocks in the context of fuel cells.[1]
- ✓ ✗ I have explained how renewable feedstocks can be sustainable.[2]
- ✓ ✗ I have explained how renewable feedstocks can be unsustainable.[3]

Key science skills

13. [Catalysis: using durable catalysts in fuel cells helps to speed up reactions and minimise energy loss, with minimal waste since catalysts can be reused many times.[1]] [An example of this is the use of carbon nanomaterial catalysts, which could last longer and hence be overall more efficient than traditional catalysts.[2]]

[Minimise the potential for accidents: the use of non-hydrogen fuels as feedstocks in fuel cells can reduce the risk of accidents.[3]] [For example, while hydrogen presents an explosion risk when stored for use in fuel cells, glucose – a safe chemical – can be used as an alternative fuel in some fuel cells.[4]]

[Prevent waste: fuel cells can be constructed from fully reusable materials and organic catalysts to leave no waste.[5]] [For example, a microbial fuel cell can be constructed from reusable containers, using soil as an electrolyte, and bacteria as a catalyst: all substances which break down naturally or can be reused.[6]]

I have explained how fuel cell innovation helps fulfil a first principle.[1]

I have given a specific example of this innovation.[2]

I have explained how fuel cell innovation helps fulfil a second principle.[3]

I have given a specific example of this innovation.[4]

I have explained how fuel cell innovation helps fulfil a third principle.[5]

I have given a specific example of this innovation.[6]

Alternative answer:

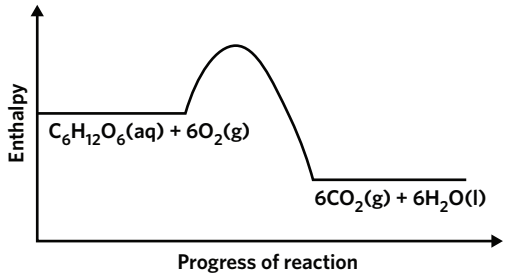
- Designing safer chemicals: the oxidation of fuels in fuel cells produces less toxic gas emissions compared with direct combustion. For example, the generation of energy via a direct ethanol fuel cell produces less harmful sulphur- and nitrogen-containing compounds, reducing overall toxicity.

FROM LESSON 12E

Questions from multiple lessons

14. a. i. $C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$

ii.



b. $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l)$

c. [If the half-cells were not separated, oxygen would react spontaneously and directly with the biomass,[1]][producing thermal energy rather than electrical energy, defeating the purpose of the cell.[2]]

I have explained that the reactants would spontaneously and directly react.[1]

I have explained that electrical energy would not be produced.[2]

d. i. $E_{cell} = E^0$(reduction: most positive value) $- E^0$(oxidation: least positive value)

$E_{cell} = +0.80\text{ V} - (-0.25\text{ V})$

$E_{cell} = +1.05\text{ V}$

ii. $2Ag^+(aq) + Ni(s) \rightarrow 2Ag(s) + Ni^{2+}(aq)$

iii. The MFC oxidises biomass, a renewable feedstock, whereas the $Ag^+(aq)\ |\ Ag(s)\ \|\ Ni^{2+}(aq)\ |\ Ni(s)$ galvanic cell oxidises nickel metal, a non-renewable feedstock.

Alternative answer:

The MFC is cheaper to operate than the $Ag^+(aq)\ |\ Ag(s)\ \|\ Ni^{2+}(aq)\ |\ Ni(s)$ galvanic cell, as biomass and bacteria are generally less expensive than nickel and silver.

FROM LESSONS 1C, 1D, 3B & 3D

Chapter 3 review

Multiple choice

1. D. According to the electrochemical series,

$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)\quad E^0 = +0.34\text{ V}$

$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)\quad E^0 = -0.14\text{ V}$

The strongest oxidising agent, $Cu^{2+}(aq)$, will react with the strongest reducing agent, Sn(s).

Therefore, the reactions occurring at each electrode are as follows:

Anode (−): $Sn(s) \rightarrow Sn^{2+}(aq) + 2e^-$

Cathode (+): $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

Electrons flow from the site of oxidation (anode) to the site of reduction (cathode) – that is, from the Sn electrode to the Cu electrode. Anions migrate towards the anode, Sn^{2+}/Sn half-cell. Cations migrate towards the cathode, Cu^{2+}/Cu half-cell.

2. A. The strongest oxidising agent, $Cu^{2+}(aq)$, is reduced at the cathode. The strongest reducing agent, Sn(s), is oxidised at the anode.

3. B. $E_{cell} = E^0$(oxidising agent half-cell) $- E^0$(reducing agent half-cell)

$E_{cell} = +0.34\text{ V} - (-0.14\text{ V})$

$E_{cell} = +0.48\text{ V}$

4. A. Since Fe is a reducing agent, a reaction may be predicted to occur if the solution contains an oxidising agent higher on the electrochemical series, i.e. with a higher E^0 than Fe.

$Pb^{2+}(aq)/Pb(s)\quad E^0 = -0.13\text{ V}$

$Ni^{2+}(aq)/Ni(s)\quad E^0 = -0.23\text{ V}$

$Fe^{2+}(aq)/Fe(s)\quad E^0 = -0.44\text{ V}$

$Zn^{2+}(aq)/Zn(s)\quad E^0 = -0.76\text{ V}$

According to the series given, only the beakers containing $Pb^{2+}(aq)$ and $Ni^{2+}(aq)$ will react with the iron strip.

5. C. Wastewater and CO_2 are renewable waste products that are continually produced by humans. Although carbon nanoparticles are non-renewable, the tiny quantity required for fuel cells means they can be produced at a greater rate than they are used. Bioethanol sourced from food crops is likely to be unsustainable, considering the high demand for food and fuel worldwide and the limited land area available.

6. C. In a fuel cell, oxygen is (almost) always reduced at the cathode, and the fuel is always oxidised at the anode. Only the equation in option C shows the reduction of oxygen.

7. C. According to oxidation numbers:

$+1\ -1 \qquad +1\ -2 \qquad 0$

$2H_2O_2(g) \rightarrow 2H_2O(l) + O_2(g)$

The oxidation number of oxygen has both decreased from −1 to −2 and increased from −1 to 0, as H_2O_2 has been reduced to H_2O and oxidised to O_2.

8. C. The recharging equation is the reverse of the discharging reaction:

$V^{3+}(aq) + VO^{2+}(aq) + H_2O(l) \rightarrow VO_2^+(aq) + 2H^+(aq) + V^{2+}(aq)$

The only atom that changes oxidation number(s) in this reaction is V, which decreases during reduction and increases during oxidation; this eliminates options A and B. VO_2^+ is a product in the recharge, and so cannot be the oxidising agent, therefore option D is also not viable. VO^{2+} is oxidised to VO_2^+, meaning the oxidation number of V increases from +4 to +5, and VO^{2+} is therefore the reducing agent.

9. B. Both types of cells produce energy, so the reaction is exothermic. Electrons are consumed (during reduction) at the positive electrode; they are released (during oxidation) at the negative electrode. In fuel cells, the oxidising agent and reducing agent are stored outside the cell. The electrodes are in contact with reactants and the electrolyte. Reactive electrodes will need to be replaced in a galvanic cell, but fuel cell electrodes are not reactive and do not need regular replacement.

10. D. The half-equation for the oxidation of hydrogen in a hydrogen-oxygen fuel cell depends on whether the electrolyte is acidic or basic.

Acid electrolyte: $H_2(g) \rightarrow 2H^+(aq) + 2e^-$

Alkaline electrolyte: $H_2(g) + 2OH^-(aq) \rightarrow 2H_2O(g) + 2e^-$

In both cases, per mol of hydrogen gas used, 2 mol of electrons is produced.

$n(e^-) = 2 \times n(H_2)$

$n(e^-) = 2 \times (2.9 \times 10^{-4}\ \text{mol})$

$n(e^-) = 5.8 \times 10^{-4}\ \text{mol}$

$Q = n(e^-) \times F$

$Q = (5.8 \times 10^{-4}\ \text{mol}) \times 96\,500\ \text{C mol}^{-1}$

$Q = 55.97\ \text{C}$

$I = \frac{Q}{t}$

$I = \frac{55.97\ \text{C}}{1\ \text{s}}$

$I = 56\ \text{A}$

Short answer

11. a. $Q = It$

$Q = 6.00\ \text{A} \times (12.0 \times 60 \times 60)\ \text{s}$

$Q = 2.592 \times 10^5\ \text{C}$

b. From $Q = n(e^-) \times F$,

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{2.592 \times 10^5\ \text{C}}{96\,500\ \text{C mol}^{-1}}$

$n(e^-) = 2.686\ \text{mol}$

c. At 60% efficiency:

$n(e^-)\ \text{required} = \frac{100}{60} \times n(e^-)\ \text{at 100\% efficiency}$

$n(e^-)\ \text{required} = \frac{100}{60} \times 2.686\ \text{mol}$

$n(e^-)\ \text{required} = 4.4767\ \text{mol}$

d. $H_2(g) \rightarrow 2H^+(aq) + 2e^-$

e. From the half-equation $H_2(g) \rightarrow 2H^+(aq) + 2e^-$

$n(H_2) = \frac{1}{2} \times n(e^-)\ \text{required}$

$n(H_2) = \frac{1}{2} \times 4.4767\ \text{mol}$

$n(H_2) = 2.238\ \text{mol}$

f. At SLC: $V(H_2) = n(H_2) \times V_m$

$V(H_2) = 2.238\ \text{mol} \times 24.8\ \text{L mol}^{-1}$

$V(H_2) = 56\ \text{L}$ (2 sig. figs)

12. a. [The phosphoric acid fuel cell is operating at 190 °C, whilst the predicted voltages given in the electrochemical series are obtained at 25 °C.[1]][The electrolyte is pure liquid phosphoric acid instead of aqueous phosphoric acid, so there are no mobile ions available to conduct electricity.[2]]

✓ ✗ I have identified one reason as to why the phosphoric acid fuel cell does not produce the +1.23 V predicted.[1]

✓ ✗ I have identified a second reason as to why the phosphoric acid fuel cell does not produce the +1.23 V predicted.[2]

Alternative answer:

- The electrolyte is not a 1.0 M solution, for which E^0 values are accurate.

b. $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

13. a. Fe(s)

b. i. [R: Fe(s)[1]][S: Ni(s)[2]]

✓ ✗ I have chosen an appropriate material for electrode R.[1]

✓ ✗ I have chosen an appropriate material for electrode S.[2]

Alternative answers:

- S: an inert electrode such as Pt(s) or C(s)
- S: any metal higher than Ni on the electrochemical series (Sn(s), Pb(s), Cu(s), Ag(s), Au(s))

ii. $Ni(NO_3)_2(aq)$ or $NiSO_4(aq)$ or $NiCl_2(aq)$

c. i. Chemical energy → thermal energy (heat)

ii. Chemical energy → electrical energy

14. a. i. Oxygen is continuously supplied as the oxidising agent.

Alternative answer:

- The cathode is porous.

ii. The magnesium anode needs to be replaced when it is used up, as it is not continuously supplied.

b. $n(Mg) = \frac{m}{M}$

$n(Mg) = \frac{1.83\ \text{g}}{24.3\ \text{g mol}^{-1}}$

$n(Mg) = 0.075308\ \text{mol}$ (1 MARK)

Oxidation half-equation: $Mg \rightarrow Mg^{2+} + 2e^-$

$n(e^-) = 2 \times n(Mg)$

$n(e^-) = 2 \times 0.075309$ mol

$n(e^-) = 0.150617$ mol (1 MARK)

$Q = n(e^-) \times F$

$Q = 0.150617 \text{ mol} \times 96\,500 \text{ C mol}^{-1}$

$Q = 14\,534.56$ C (1 MARK)

$t = \frac{Q}{I}$

$t = \frac{14\,534.56 \text{ C}}{1.22 \text{ A}}$

$t = 1.19 \times 10^4$ s (3 sig. figs) (1 MARK)

c. i. Considering the abundance of saltwater in the ocean, the electrolyte can be produced sustainably.

Alternative answer:

- Air is abundant, and so the oxidising agent is a sustainable material.

ii. Since magnesium is a mineral, it is non-renewable.

15. a. i. A: Negative; B: Positive

ii. From A to B

b. A fuel cell is more efficient than a petrol generator.

Alternative answers:

- Fuel cells (MCFC) do not have a net overall release of CO_2.
- Fuel cells use (possibly) renewable H_2, whereas petrol, a fossil fuel, is not renewable.

c. i. $CO_2(g) + \frac{1}{2}O_2(g) + 2e^- \rightarrow CO_3^{2-}(l)$

Alternative answer:

$2CO_2(g) + O_2(g) + 4e^- \rightarrow 2CO_3^{2-}(l)$

ii. $O_2 : CO_3^{2-}$

1 : 2 (1 MARK)

$n(O_2) = \frac{1}{2} \times n(CO_3^{2-})$

$n(O_2) = \frac{1}{2} \times 11.50$ mol

$n(O_2) = 5.75$ mol (1 MARK)

$V(O_2) = n(O_2) \times 30.8 \text{ L mol}^{-1}$

$V(O_2) = 5.75 \text{ mol} \times 30.8 \text{ L mol}^{-1}$

$V(O_2) = 177$ L (3 sig. figs) (1 MARK)

Key science skills

16. a. Green chemistry helps to preserve the health of humans, ecosystems, and the earth, to ensure that future generations can continue to access the resources and living conditions made possible by chemical innovation.

b. i. [The use of microbes in fuel cells can help to achieve Goal 6: Clean water and sanitation,[1]][because by oxidising wastewater, the cell simultaneously produces clean, treated water.[2]][CO_2-consuming fuel cells help to achieve Goal 13: Climate action,[3]][since the consumption of CO_2 by these fuel cells reduces the amount of CO_2, a greenhouse gas, in the atmosphere.[4]]

✓ ✗ I have identified a goal achieved by a first fuel cell innovation.[1]

✓ ✗ I have explained how this innovation helps to achieve this goal.[2]

✓ ✗ I have identified a goal achieved by a second fuel cell innovation.[3]

✓ ✗ I have explained how this innovation helps to achieve this goal.[4]

ii. [Although microbes are readily available and can break down extremely abundant feedstocks such as wastewater,[1]][the membranes used in many of these fuel cells are currently expensive to produce.[2]][CO_2-consuming fuel cells pose a huge climate benefit by reducing the amount of CO_2 in the atmosphere,[3]][but may not produce a sufficient voltage to meet society's massive energy demands.[4]]

✓ ✗ I have evaluated a first fuel cell innovation.[1]

✓ ✗ I have identified a challenge faced by a first fuel cell innovation.[2]

✓ ✗ I have evaluated a second fuel cell innovation.[1]

✓ ✗ I have identified a challenge faced by a second fuel cell innovation.[4]

FROM LESSON 12E

17. B. CuO was decomposed by strong heating, and the residual Cu remained in the tube after heating. The percentage by mass of Cu in the CuO was determined by dividing the mass of the residual Cu by the original mass of CuO.

$$\% \text{ Cu} = \frac{m(\text{Cu}) \text{ remaining}}{m(\text{CuO}) \text{ used}} \times 100$$

The m(Cu) remaining is determined by:

m(Cu) = m(tube and Cu) after heating − m(empty tube)

The m(CuO) used is determined by:

m(CuO) = m(tube and CuO before heating) − m(empty tube)

Since CuO has a higher molar mass than Cu, unreacted CuO will cause the students to measure a higher m(Cu) remaining, which results in a higher calculated % Cu in the CuO. Option B could therefore not be an explanation of the result as the students recorded a lower experimental % Cu in the CuO than the theoretical value.

FROM LESSONS 12A & 12B

4A Factors affecting the rate of reaction

Progress questions

1. C. For a reaction to occur, reacting molecules must collide in the right orientation and with energy equal to or greater than the activation energy.

2. C. Lower average kinetic energy of particles means fewer particles have sufficient energy to react.

3. D. The key explanation for the relationship between temperature and reaction rate is the higher proportion of particles with sufficient energy to react successfully.

4. D. Using magnesium powder instead of the piece of ribbon means the reactant particles have a greater total surface area for collisions to take place, and thus for collisions to take place successfully.

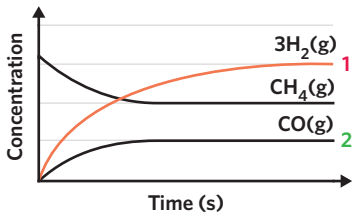
5. D. Unpolished surface (impurities) reduces chance of contact between $H^+(aq)$ and Mg(s), so fewer collisions, and thus fewer successful collisions, will occur.

6. D. Using a lump instead of powder decreases the surface area available for collisions to occur.

Deconstructed

7. A **8.** D

9.



✓ ✗ I have shown that the concentration of $H_2(g)$ will increase.[1]

✓ ✗ I have shown that three times as much $H_2(g)$ will be produced in comparison to CO(g).[2]

Exam-style

10. B. Larger surface area of iron pieces results in higher reaction rate.

11. True: III; V
False: I; II ; IV
Three marks if all correct, two marks if four correct, one mark if two or three correct.

12. a. [Increasing the temperature will increase the rate of O_2 production.[1]][There will be an increased average kinetic energy of all molecules, leading to increased frequency of collisions.[2]][There will also be an increased proportion of collisions that exceed the activation energy threshold (i.e. that are successful).[3]]

✓ ✗ I have identified the increased rate of O_2 production.[1]

✓ ✗ I have explained that there will be an increase in frequency of collisions.[2]

✓ ✗ I have explained that there will be a higher proportion of successful collisions.[3]

b. 1.00 L $H_2O_2(aq) \rightarrow$ 10.0 L $O_2(g)$ at standard laboratory conditions

$n(O_2) = \frac{V}{V_m}$

$n(O_2) = \frac{10.0\text{ L}}{24.8\text{ L mol}^{-1}}$

$n(O_2) = 0.4032\text{ mol}$

From the equation $2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g)$

$n(H_2O_2) = 2 \times n(O_2)$

$n(H_2O_2) = 0.8064\text{ mol}$ (1 MARK)

$m(H_2O_2) = n \times M$

$m(H_2O_2) = 0.8064\text{ mol} \times 34.0\text{ g mol}^{-1}$

$m(H_2O_2) = 27.42\text{ g}$

$c(H_2O_2) = 27.4\text{ g L}^{-1}$ (1 MARK)

c. [Take a known amount (mass or volume) of H_2O_2 solution.[1]][Measure the $V(O_2)$ produced over time using a gas syringe or another appropriate gas collection apparatus.[2]][Construct a graph of $V(O_2)$ produced versus time and use the gradient to determine the rate of decomposition.[3]]

✓ ✗ I have explained that a known amount of H_2O_2 should be obtained.[1]

✓ ✗ I have explained that the volume of oxygen produced over time should be measured using a gas collection apparatus.[2]

✓ ✗ I have explained that a graph of oxygen produced versus time should be produced.[3]

13. a. The rate can be measured by first measuring either the change in mass of the beaker or the volume of CO_2 produced over a set time interval, and then plotting the change against time.

b. Surface area (or particle size of $CaCO_3$)

c. [The reaction rate will be faster in beaker A.[1]][The higher concentration of HCl will increase the frequency of collisions between reactant particles.[2]]

✓ ✗ I have identified which beaker will have the faster reaction rate.[1]

✓ ✗ I have explained my selection in terms of collision theory.[2]

d. [For a reaction to occur, particles must collide with energy greater than E_a. That is, they must collide with sufficient energy to break existing bonds within reactants.[1]][Particles must also collide in a particular orientation.[2]]

✓ ✗ I have explained that particles must collide with sufficient energy.[1]

✓ ✗ I have explained that particles must collide with the correct orientation.[2]

14. A. The combustion of ethanol from a test tube requires that the test tube be gently heated to vaporise the ethanol, which then burns as the open end of the test tube is held to a flame. Adding 2 mL of dilute NaOH will slow down release of ethanol vapour for combustion because ethanol molecules form hydrogen bonds with water molecules. Option B overlooks the fact that a larger exposed surface of ethanol provided by doubling the diameter of the test tube will increase the rate of evaporation of ethanol at the surface and thus increase the rate of the combustion reaction.

Key science skills

15. a. [Chris has generally shown a good understanding of collision theory, however, he has confused rate and extent. At the end of his last sentence he should say '. . . the greater the amount of H_2 gas that will be produced per second.'[1]][Collision theory refers to the mechanism and rate of the reaction, not to the final amount of product. The amount of product depends on the amounts of the reactants, not the frequency of collisions.[2]]

✓ ✗ I have evaluated Chris' understanding of the chemistry relevant to the investigation.[1]

✓ ✗ I have explained my reasoning with respect to collision theory.[2]

b. No, the concentration of HCl is the independent variable as it is being varied to test its effect on the rate of the reaction. The volume of hydrogen produced is the dependent variable because it depends on the concentration of HCl.

c. [The use of the stirrer[1]][keeps the reactants mixed, so the reaction can take place at an optimum rate.[2]]

✓ ✗ I have identified a feature of the experimental setup that is designed to improve the accuracy of the results.[1]

✓ ✗ I have justified my choice.[2]

Alternative answers:

- The injection of HCl via the syringe and the use of seals ensure that no H_2 gas escapes.
- Filming the syringe and stopwatch means students can replay the film at a slower speed and more accurately record the volume and time simultaneously.

d. [Given the bubbling had not stopped at the end of the timing, it is reasonable to assume the reaction had not yet reached completion in that time. This is because with more dilute acid, the reaction occurred at a slower rate.[1]][The variable that was not considered was the temperature of the reaction mixture.[2]] [The temperature could be controlled by placing the reaction vessel in a water bath that has a consistent temperature.[3]]

✓ ✗ I have explained the differences in the rate of bubbling in each flask.[1]

✓ ✗ I have identified the key uncontrolled variable.[2]

✓ ✗ I have explained how this variable could be controlled.[3]

e. [Chris could have concluded that as the steepness of the graphs increased with increasing HCl concentration, the rate of reaction is related to the concentration of HCl. That is, the rate of reaction increases with increasing HCl concentration.[1]] [In relation to his hypothesis that the greater the concentration of HCl, the greater the amount of H_2 produced, while the graphs appear to support this, the fact that the reaction was not complete for the three more dilute solutions means that this hypothesis has not been supported.[2]]

✓ ✗ I have explained that Chris can observe a relationship between the rate of reaction and the concentration of HCl used.[1]

✓ ✗ I have used Chris' observations and graphs to explain that his hypothesis has not been supported.[2]

f. Answers may vary.
Example:

i. Another question could be: What is the relationship between the rate of the reaction and the temperature of the reactants? (1 MARK)

ii. Step 1. Select a particular concentration of HCl and mass of Mg to trial.

Step 2. Place the apparatus in a water bath set at 20 °C and run the experiment as Chris did in his first trial, but keep timing until the reaction ceases.

Step 3. Using the same concentration of HCl and mass of Mg, repeat step 2 at least 4 times at different temperatures. (1 MARK)

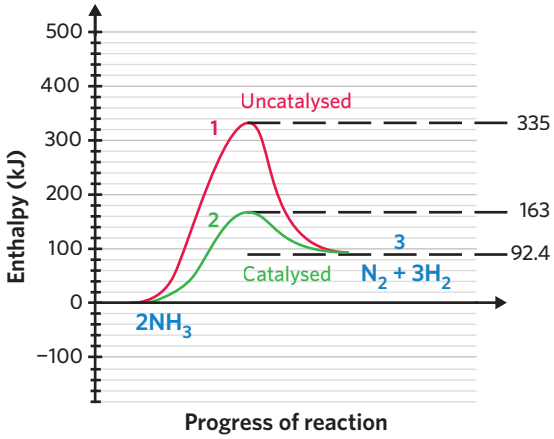
Step 4. If there is time, repeat steps 2 and 3 using a different concentration of HCl and the same mass of Mg.

Step 5. Record all observations and graph all results. (1 MARK)

FROM LESSONS 12B, 12C, 12D & 12E

Questions from multiple lessons

16. a.



✓ ✗ I have drawn the correct shape for the uncatalysed profile.[1]

✓ ✗ I have drawn the correct shape for the catalysed profile.[2]

✓ ✗ I have drawn the products in the correct location.[3]

b. [Since using the tungsten catalyst requires less energy for the reaction to proceed,[1]][there will be a higher proportion of particles with sufficient energy to break the bonds within reactants.[2]]

- ✓ ✗ I have identified that using tungsten as a catalyst provides a reaction pathway with lower activation energy.[1]
- ✓ ✗ I have explained that there will be a higher proportion of successful collisions.[2]

FROM LESSONS 1D & 2A

17. a. [Zinc acts as a sacrificial anode by undergoing a redox reaction with oxygen more readily than iron.[1]][Therefore, the zinc coating will be oxidised preferentially over the iron nail, protecting it from rusting.[2]][The iron in the uncoated nails will be oxidised by oxygen immediately, causing the nails to rust more quickly.[3]]

- ✓ ✗ I have identified that zinc is oxidised before iron.[1]
- ✓ ✗ I have explained how the coating slows the rusting process.[2]
- ✓ ✗ I have explained that the iron in the uncoated nails will be oxidised immediately.[3]

b. [Breaking the nail into smaller pieces increases the surface area of the pieces.[1]][Creating a greater surface area for reactant particles to collide will result in more frequent collisions, and hence more frequent successful collisions.[2]][Therefore, the rate of the reaction would increase.[3]]

- ✓ ✗ I have identified the effect of the change on the reactant particles.[1]
- ✓ ✗ I have used collision theory to explain the effect on the rate of the reaction.[2]
- ✓ ✗ I have identified the effect on the rate of reaction.[3]

c. [Nails exposed to the sun are likely to be hotter than those in the shade, meaning the reactant particles would have a greater average kinetic energy.[1]][This means a greater proportion of particles can collide with sufficient energy to meet the requirements of the activation energy, thereby increasing the rate of reaction.[2]][Furthermore, there would be an increase in the frequency of collisions, also resulting in an increased reaction rate.[3]]

- ✓ ✗ I have identified the effect of the conditions on the reactant particles.[1]
- ✓ ✗ I have used collision theory to explain the effect of the energy of reactant particles on reaction rate.[2]
- ✓ ✗ I have used collision theory to explain the effect of the number of collisions on reaction rate.[3]

FROM LESSONS 3A & 3C

4B Catalysts

Progress questions

1. C. In reversible reactions, catalysts lower the activation energy for both the forward and reverse reactions by the same amount.

2. B. A catalyst provides an alternative reaction pathway with a lower activation energy, meaning a greater proportion of reactant particles have sufficient energy to collide successfully.

3. D. The peak of the energy profile diagram will decrease in height to represent the lower activation energy of the catalysed reaction.

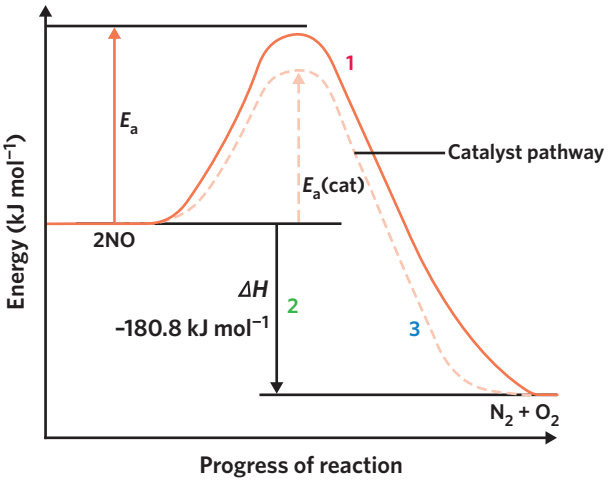
4. B. Options A and C can be ruled out as a catalyst does not affect the energies of the products or reactants. Option D can be ruled out as the energy profile represents an endothermic reaction.

5. D. From the graph, the activation energy of the uncatalysed reaction is approximately 90 kJ mol^{-1} and the ΔH of the catalysed reaction is −50 kJ mol^{-1}. Note: ΔH is the same for both the catalysed and uncatalysed reactions.

Deconstructed

6. A **7.** B

8.



- ✓ ✗ I have drawn the profile for an exothermic reaction.[1]
- ✓ ✗ I have fully labelled the diagram, showing the overall change in enthalpy of the reaction.[2]
- ✓ ✗ I have drawn a catalysed pathway with a lower activation energy.[3]

Exam-style

9. a. [Manganese(IV) oxide would increase the rate of hydrogen peroxide decomposition the most[1]][as it results in the greatest volume of oxygen evolved in a given period of time.[2]]

- ✓ ✗ I have stated which catalyst increased the rate of decomposition the most.[1]
- ✓ ✗ I have given a reason for my choice.[2]

b. [By using a powdered catalyst instead of a solid, there is more surface area available for reactants to bind to,[1]][resulting in a greater chance of reactants coming into contact with the surface of the catalyst.[2]]

✓ ✗ I have described the increased surface area of powdered catalysts.[1]

✓ ✗ I have explained that powdered catalysts allow for a greater chance of reactants coming into contact with the surface of the catalyst.[2]

Key science skills

10. a. [Use the same volume of H_2O_2 in each trial.[1]][Use the same concentration of H_2O_2 in each trial.[2]][Use the same amount in moles of both catalysts.[3]]

✓ ✗ I have identified an improvement.[1]

✓ ✗ I have identified a second improvement.[2]

✓ ✗ I have identified a third improvement.[3]

Alternative answers:

- Use a device with better insulation such as a calorimeter to minimise heat loss.
- Investigate more than two different catalysts.
- Repeat the trials to reduce the effects of random error.
- Use a mechanical stirrer to ensure thorough mixing of reactants.
- Use catalysts of the same phase.

b. Different catalysts will have no effect on the molar heat of reaction since the molar enthalpy of the decomposition reaction of hydrogen peroxide is independent of the catalyst used.

Alternative answers:

- The same molar heat of reaction should be found irrespective of the catalyst used, assuming all other variables are controlled.
- A catalyst has no effect on the relative enthalpies of the reactants and products, and hence does not affect the molar heat of reaction.
- The same molar enthalpy should be determined for the decomposition of H_2O_2, irrespective of the catalyst used.

c. If investigating the effect of different catalysts on the molar enthalpy of decomposition, the only variable changed should be the type of catalyst used. The results presented were inconclusive because variables that should have been controlled, such as the concentration of H_2O_2, were not kept constant.

Alternative answer:

- The conclusion that the different temperatures for the two trials verify that the molar enthalpy of decomposition depends on the catalyst used is invalid because $n(H_2O_2)$ reacting in Trial 2 is four times the $n(H_2O_2)$ reacting in Trial 1, causing a greater temperature change.

FROM LESSONS 12B, 12D & 12E

Questions from multiple lessons

11. a. $\Delta H = \sim -230$ kJ mol^{-1}

b. $E_a = +360$ kJ mol^{-1}

c. i. [Catalysts bind to reactants, thereby providing an alternative reaction pathway.[1]][This alternative reaction pathway has a lower activation energy than that of the uncatalysed reaction.[2]]

✓ ✗ I have identified that catalyst provide an alternative reaction pathway.[1]

✓ ✗ I have explained that this alternative pathway has a lower activation energy.[2]

ii. [Catalysts do not have any effect on the energy of the products or the reactants.[1]][Therefore, given ΔH is the difference in enthalpy between the products and reactants, ΔH would not be affected by the use of a catalyst.[2]]

✓ ✗ I have explained that catalysts do not affect the energy of the products or reactants.[1]

✓ ✗ I have explained that ΔH would not be affected by a catalyst.[2]

FROM LESSON 1D

Chapter 4 review

Multiple choice

1. D. A catalyst weakens the bonds within reactant particles by binding to them, which results in the lowering of the activation energy of the reaction.

2. B. By using powdered reactants, there is a greater overall surface area for reactant particles to collide, and thus a higher frequency of collisions (higher number of collisions per unit time). In turn, there is a higher frequency of successful collisions (higher number of successful collisions per unit time), producing a faster rate of reaction.

3. C. Catalysts have no effect on the change in enthalpy or yield of a reaction, and are not used up in a reaction. However, they do provide an alternative reaction pathway with a lower activation energy, thereby increasing the proportion of particles with sufficient energy to react.

4. C. The first collision is successful as the reactants collide with the correct orientation.

5. A. The poisoning of the catalyst means it will no longer be able to bind to reactants and provide the reaction pathway with a lower activation energy. Hence, the reaction rate will decrease and remain constant at that lower rate.

6. C. According to each graph, the concentration of product C is constant up to time t_1, and since a catalyst has no effect on the yield of a reaction, the amount of product C will not change when the catalyst stops working, and in turn, the concentration of product C will not change.

7. B. The reactions in trials 1 and 2 are carried out using the same concentration of HCl, however, the reaction in trial 1 is carried out at a higher temperature and should therefore proceed more quickly than that of trial 2. The reaction in trial 3 occurs at the highest temperature and with the highest concentration of HCl, and should therefore proceed most quickly.

8. D. The platinum gauze has more surface area available for catalysing the reaction.

9. D. The energy profile diagram with the lowest activation energy should represent the reaction that occurs most quickly at a given temperature and pressure.

10. B. Statement I: the activation energy for the forward reaction is equal to $b - c$. This will be greater than $c - b$, which instead gives a negative value.

Statement II: For the uncatalysed reaction, b represents the activation energy for the reverse reaction. However, since a suitable catalyst is used, the activation energy for both the forward and reverse reactions will be lowered. Hence, the activation energy for the reverse reaction will be less than b.

Statement III: For the uncatalysed reaction, a represents the activation energy for the forward reaction. However, since a suitable catalyst is used, the activation energy of the forward reaction will be lowered, and will thus be less than a.

Therefore, only statement III is correct.

Short answer

11. a. [When the concentration of hydrogen gas increases, the frequency of collisions between hydrogen and iodine molecules increases.[1]][This results in an increased frequency of successful collisions, which produces a faster rate of reaction.[2]]

✓ ✗ I have identified the effect of increased hydrogen gas concentration on collisions between reactants.[1]

✓ ✗ I have explained the effect of increased frequency of collisions on the rate of reaction.[2]

b. [Increasing the pressure of the system leads to a higher concentration of reactant gas molecules in the reaction vessel.[1]] [This increased concentration results in an increase in the frequency of collisions between reactant particles, in turn causing an increase in the frequency of successful collisions, which is likely to increase the rate of reaction.[2]]

✓ ✗ I have identified the effect of increased pressure on the concentration of reactants.[1]

✓ ✗ I have explained the effect of the concentration of reactants on the rate of reaction.[2]

12. [The catalyst provides an alternative reaction pathway with a lower activation energy[1]][by lowering the amount of energy required to break the bonds in the reactants.[2]][Hence, there is a greater proportion of reactants with the necessary energy to react,[3]][and therefore an increase in the proportion of successful collisions.[4]]

✓ ✗ I have explained that a catalyst lowers the activation energy of the reaction.[1]

✓ ✗ I have explained how catalysts lower activation energy.[2]

✓ ✗ I have explained that a greater proportion of reactants will have the necessary energy to react.[3]

✓ ✗ I have explained that there is a greater proportion of successful collisions.[4]

13. a. [The reaction should be carried out in a closed system[1]] [to prevent gas from escaping the reaction vessel.[2]]

✓ ✗ I have stated that the reaction should be carried out in a closed system.[1]

✓ ✗ I have justified my answer.[2]

b. [At higher temperatures, there is an increased average kinetic energy of all molecules, leading to increased frequency of collisions between X molecules.[1]][There is also an increased proportion of collisions that exceed the activation energy threshold, i.e. that are successful.[2]][Together, more frequent collisions and a greater proportion of successful collisions result in an increased rate of reaction.[3]]

✓ ✗ I have explained the effect of temperature on the frequency of collisions.[1]

✓ ✗ I have explained the effect of temperature on the proportion of successful collisions.[2]

✓ ✗ I have explained the effect on the rate of reaction.[3]

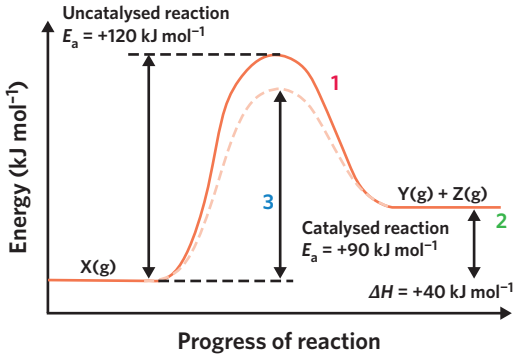
c. [Catalysts increase the rates of both the forward and reverse reactions to the same extent.[1]][As a result, the yield of Z from the catalysed reaction will be the same as the yield from the uncatalysed reaction.[2]]

✓ ✗ I have identified the effect of catalysts on the rates of the forward and reverse reactions.[1]

✓ ✗ I have explained why catalysts do not affect the yield of reactions.[2]

d. i. The activation energy of a reaction is the minimum amount of energy required for a reaction to proceed.

ii.



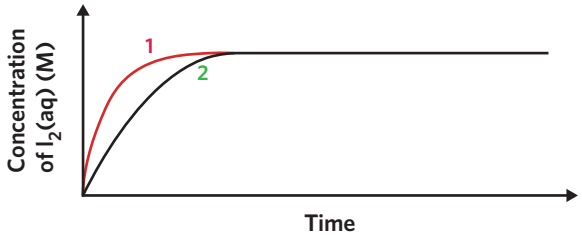
- I have drawn the profile for an endothermic reaction.[1]
- I have fully labelled the diagram showing the overall change in enthalpy of the reaction.[2]
- I have drawn a catalysed pathway with a lower activation energy.[3]

iii. $E_a = +50$ kJ mol^{-1}

14. a. [Since peroxydisulfate ions and iodide ions are both negatively charged, they will repel each other, meaning the reaction occurs slowly.[1]][The positive charges on iron(II) or iron(III) ions will attract these negative ions, allowing bonds to form between reactants more readily.[2]]

- I have identified the interactions between two negatively charged ions.[1]
- I have explained the interactions between ions of opposite charge.[2]

b.



- I have drawn a curve that plateaus more quickly than the uncatalysed curve.[1]
- I have drawn a curve that plateaus at the same concentration as the uncatalysed curve.[2]

15. a. [Increased temperature[1]][and increased pressure of the reaction system[2]]

- I have identified one condition that will increase the rate of sulfur dioxide oxidation.[1]
- I have identified a second condition that will increase the rate of sulfur dioxide oxidation.[2]

Alternative answer:

- Increased concentration of reactants and addition of a catalyst

b. [In the Contact Process, vanadium(V) pentoxide acts a catalyst, increasing the rate of reaction.[1]][It does this by binding to the reactants and weakening the bonds within the molecules, thereby providing an alternative reaction pathway with a lower activation energy.[2]][In industry, this serves to reduce the energy input and (consequently) the costs required to produce the same amount of sulfuric acid.[3]]

- I have stated the role of vanadium(V) pentoxide.[1]
- I have explained how vanadium(V) pentoxide catalyses the reaction.[2]
- I have linked the role of vanadium(V) pentoxide to the industrial benefits.[3]

c. Vanadium can exist in four different oxidation states (+2, +3, +4, and +5).

Key science skills

16. a. [Catalytic converters use a honeycomb structure because it provides a large surface area for the metal catalyst coating to bind to the toxic reactants in the exhaust gases,[1]][thereby more effectively increasing the proportion of particles that can react in the pathway with lower activation energy, in turn more effectively increasing the rate of catalytic conversion.[2]]

- I have identified the effect of the honeycomb structure on the surface area of the catalyst.[1]
- I have explained the effect of increased surface area on the rate of catalytic conversion.[2]

b. [The use of precious metals.[1]][Precious metals like platinum are very expensive, making catalytic converters very expensive to produce.[2]]

- I have identified the key economic concern.[1]
- I have explained why this is an economic concern.[2]

c. i. [Lead from leaded petrol coats the surface of the catalyst,[1]][reducing the surface area available for the catalysis of toxic gases.[2]]

- I have stated that lead coats the surface of the catalyst.[1]
- I have explained the effect of the lead coating on the surface area of the catalyst, and the consequences for catalysis.[2]

ii. [The 'poisoning' of catalytic converters results in increased levels of carbon monoxide in the air.[1]][Carbon monoxide contributes to the enhanced greenhouse effect, which is linked to global warming.[2]][The 'poisoning' of catalytic converters also results in increased levels of nitrogen monoxide in the air.[3]][Nitrogen monoxide reacts with water, oxygen and other chemicals in the atmosphere to form acid rain, which can cause extensive damage to vegetation and marine ecosystems.[4]]

- I have identified the increased levels of carbon monoxide.[1]
- I have explained the effect of increased carbon monoxide on the environment.[2]
- I have identified the increased levels of nitrogen monoxide.[3]
- I have explained the effect of increased nitrogen monoxide on the environment.[4]

FROM LESSON 12B

5A Equilibrium reactions

Progress questions

1. C. Permitting they occur in a closed system, any reversible reaction can reach equilibrium.

2. A. The combustion of methane is an irreversible reaction because the carbon dioxide gas and water vapour released cannot be retained and converted into methane and oxygen gas again.

3. B. Irreversible reactions are represented by a unidirectional arrow (→).

4. D. The total number of reactant molecules present in a reaction vessel alone does not provide information about the proportion of reactant molecules that have been converted into products.

5. A. How quickly a chemical reaction proceeds has no effect on the proportion of reactants that will form products, and therefore has no effect on the extent of a chemical reaction.

6. D. The extent of a chemical reaction refers to the degree to which reactants are converted into products.

7. C. $\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$\text{percentage yield} = \frac{40\text{ g}}{50\text{ g}} \times 100\%$

$\text{percentage yield} = 80\%$

8. C. The value of K provides information about the extent to which a reaction has proceeded towards the products or reactants at equilibrium.

9. C. When a system is in dynamic equilibrium, the forward and reverse reactions are occurring at the same rate.

10. B. When a reaction system is at dynamic equilibrium, the forward and reverse reactions are occurring at the same rate. Therefore, both the endothermic and exothermic reactions occur at the same rate, resulting in no net change in the temperature of the system.

11. D. From the graph, the concentration of Cl_2 at time t_0 is approximately 0.75 M.

12. C. At 100 seconds, the concentrations of all species present plateau, meaning the system has reached dynamic equilibrium. Therefore, the concentrations of all species will remain constant.

13. A. From the graph, there is a 1:1:1 ratio for the changes in concentration of each species present.

Deconstructed

14. C

15. A

16. [Initially, the rate of the forward reaction is decreasing[1]][and the rate of the reverse reaction is increasing.[2]][At 120 seconds, the system reaches dynamic equilibrium, and the rates of the forward and reverse reactions become equal and remain equal thereafter.[3]]

- ✓ ✗ I have identified how the rate of the forward reaction changes initially.[1]
- ✓ ✗ I have identified how the rate of the reverse reaction changes initially.[2]
- ✓ ✗ I have explained that the rates of the forward and reverse reactions are equal once the system reaches equilibrium.[3]

Exam-style

17. C. Since both the forward and reverse reactions are occurring at time t_0, both $XY_2(g)$ and $X_2Y_4(g)$ must have been present in the reaction vessel initially.

18. B. Whilst the mass of PCl_5 will decrease, the law of conservation of mass implies that the total mass of the gas mixture will not change.

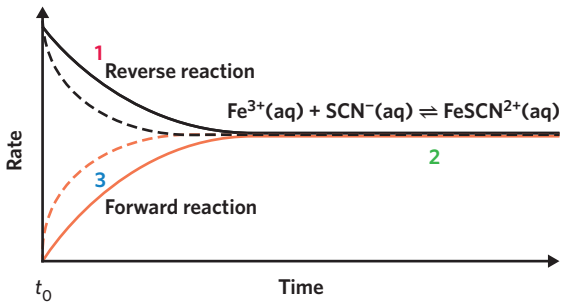
19. a. [At equilibrium, the concentrations of Fe^{3+}, SCN^-, and $FeSCN^{2+}$ are all constant,[1]][and the rates of the forward and reverse reactions are equal.[2]]

- ✓ ✗ I have identified that the concentrations of all species present are constant.[1]
- ✓ ✗ I have identified that the rates of the forward and reverse reactions are equal.[2]

b. [A catalyst would have no effect on the yield of the $FeSCN^{2+}$ ion,[1]][because catalysts only affect the rate of reaction, not the extent of the reaction.[2]][Although the reaction may reach equilibrium more quickly, the position of equilibrium would not be affected.[3]]

- ✓ ✗ I have identified that a catalyst would have no effect on the yield of the $FeSCN^{2+}$ ion.[1]
- ✓ ✗ I have explained that catalysts only affect the rate of the reaction.[2]
- ✓ ✗ I have explained that the position of equilibrium would not change.[3]

c.



- ✓ ✗ I have drawn a rate-time graph showing the reverse reaction rate decreasing and the forward reaction rate increasing.[1]
- ✓ ✗ I have shown that the rates of the forward and reverse reactions eventually become equal.[2]
- ✓ ✗ I have drawn catalysed curves (dotted lines) that show the system reaching equilibrium more quickly.[3]

Key science skills

20. a. i. Pressure: 400 atm, Temperature: 100 °C

ii. Using lower temperatures results in a slower rate of ammonia production.

iii. A catalyst could be used to speed up the rate of reaction.

b. [Using equipment at higher pressures results in increased safety risks as the equipment may not be able to withstand the increased pressure.[1]][Additionally, the operating costs are higher as more energy is required to maintain higher pressures.[2]]

✓ ✗ I have identified one disadvantage associated with using higher pressures.[1]

✓ ✗ I have identified a second disadvantage associated with using higher pressures.[2]

FROM LESSONS 12B & 12C

Questions from multiple lessons

21. a. [In N_2 and O_2, the oxidation states of nitrogen and oxygen are both 0. In NO, however, the oxidation state of nitrogen is +2 whereas the oxidation state of oxygen is −2.[1]][Therefore, nitrogen has been oxidised and oxygen has been reduced, making the formation of nitrogen monoxide a redox reaction.[2]]

✓ ✗ I have identified the oxidation states of all species on both sides of the reaction.[1]

✓ ✗ I have linked my answer to the question.[2]

b. i. [Since only NO(g) is initially present in the container the rate of the reverse reaction ($2NO(g) \rightarrow N_2(g) + O_2(g)$) will decrease and the rate of the forward reaction ($N_2(g) + O_2(g) \rightarrow 2NO(g)$) will increase from 0 as the system approaches equilibrium.[1]][Thus, the rate of the reverse reaction will always be greater than the rate of the forward reaction as the system approaches equilibrium.[2]]

✓ ✗ I have explained the changes in the rates of the forward and reverse reactions as the system reaches equilibrium.[1]

✓ ✗ I have linked my answer to the question.[2]

ii. The rates of the forward and reverse reactions are equal at equilibrium.

FROM LESSON 3A

5B Calculating equilibrium constants

Progress questions

1. D. The value of K for a reaction may change with temperature due to more or less energy being available to the system.

2. B. $K = \frac{[NH_3]^2}{[N_2][H_2]^3}$

$K = \frac{1.0^2\ M^2}{1.0\ M \times 1.0^3\ M^3}$

$K = \frac{1.0\ M^2}{1.0\ M^4}$

$K = 1.0\ M^{-2}$

3. D. The expression for the equilibrium constant is given by $\frac{[products]}{[reactants]}$ or $\frac{[right]}{[left]}$

Therefore, $K = \frac{[NH_3]^2}{[H_2]^3[N_2]}$

4. C. The value of K is only affected by changes in temperature.

5. B. An increase in temperature will always increase the rate of a reaction, however, for an exothermic reaction, the value of K will decrease as the equilibrium will shift towards the reactants.

6. A. The value of Q gives information about the extent to which a reaction has proceeded.

7. A. The system will favour the formation of products by proceeding in the forward direction in order to reach equilibrium.

8. C. At equilibrium, the value of Q is equivalent to the value of K.

Deconstructed

9. C **10.** C

11. D. $K = \frac{[SO_3]^2}{[SO_2]^2[O_2]}$

$[SO_3] = \sqrt{K \times [SO_2]^2[O_2]}$

$[SO_3] = \sqrt{1.75\ M^{-1} \times (0.12\ M)^2 \times 0.16\ M}$

$[SO_3] = \sqrt{4.03 \times 10^{-3}\ M^2}$

$[SO_3] = 6.3 \times 10^{-2}\ M$

Exam-style

12. A. $K = \left(\frac{[C]}{[A][B]}\right)^2$

$K = (0.050\ M^{-1})^2$

$K = 0.0025\ M^{-2}$

13. C. $K_{forward} = \left(\frac{[IBr]^2}{[Br_2][I_2]}\right)^2$

$K_{forward} = (1.2 \times 10^2)^2$

$K_{reverse} = \frac{1}{(1.2 \times 10^2)^2}$

$K_{reverse} = 6.9 \times 10^{-5}$

14. B. $K = \frac{[NO_2]^2}{[N_2O_4]}$

$3.15\ M = \frac{[NO_2]^2}{0.350\ M}$

$[NO_2]^2 = 3.15\ M \times 0.350\ M$

$[NO_2] = \sqrt{3.15\ M \times 0.350\ M}$

$[NO_2] = 1.05\ M$

15. a. $K = \frac{[HCN][CO_2][H_2]}{[CO]^2[NH_3]}$

b. i. $Q = \frac{(13.40\ M) \times (15.30\ M) \times (19.20\ M)}{(0.163\ M)^2 \times (40.00\ M)}$

$Q = 3704$ (1 MARK)

Since $Q > K$, the system will establish equilibrium by increasing the proportion of reactants, meaning a net backward reaction will occur to establish equilibrium. (1 MARK)

ii.

Conc. (M)	$2CO(g) + NH_3(g) \rightleftharpoons HCN(g) + CO_2(g) + H_2(g)$				
n	2	1	1	1	1
I	0.163	40.00	13.40	15.30	19.20
C	$+(2 \times 5.60)$	+5.60	−5.60	−5.60	−5.60
E	11.36	45.60 (1 MARK)	7.80	9.70	13.60

At equilibrium, $[NH_3] = 45.60$ M

$n(NH_3) = c \times V$

$n(NH_3) = 45.60 \text{ M} \times 7000 \text{ L}$

$n(NH_3) = 3.192 \times 10^5 \text{ mol}$ (1 MARK)

$m(NH_3) = n \times M$

$m(NH_3) = (3.192 \times 10^5 \text{ mol}) \times (14.0 \text{ g mol}^{-1} + 3 \times 1.0 \text{ g mol}^{-1})$

$m(NH_3) = 5.43 \times 10^6 \text{ g}$ (1 MARK)

iii.

Conc. (M)	$2CO(g) + NH_3(g) \rightleftharpoons HCN(g) + CO_2(g) + H_2(g)$				
n	2	1	1	1	1
I	0.163	40.00	13.40	15.30	19.20
C	$+(2 \times 13.399)$	+13.399	−13.399	−13.399	−13.399 (1 MARK)
E	26.961	53.399	0.00100	1.901	5.801 (1 MARK)

$$K = \frac{[HCN][CO_2][H_2]}{[CO]^2[NH_3]}$$

$$K = \frac{(0.00100 \text{ M}) \times (1.901 \text{ M}) \times (5.801 \text{ M})}{(26.961 \text{ M})^2 \times (53.399 \text{ M})}$$

$K = 2.84 \times 10^{-7}$ (no units) (1 MARK)

ii. [As the temperature decreased from T_1 to T_2, the value of K decreased also.[1]][Therefore, since K decreased with decreasing temperature, the production of HCN is likely to be endothermic.[2]]

✓ ✗ I have described the relationship between the temperature change and the new value of K.[1]

✓ ✗ I have determined whether the reaction is exothermic or endothermic.[2]

c. [Although the second method was observed to proceed at a much higher rate, the equilibrium constant serves as an indicator of the extent of a reaction, and is not necessarily linked to the rate of reaction.[1]][Hence, it is not possible to determine anything about the relative value of the equilibrium constant for the reaction in the second method.[2]]

✓ ✗ I have explained that K is only an indicator of the extent of a reaction, not the rate of reaction.[1]

✓ ✗ I have linked my answer to the question.[2]

Key science skills

16. a. $$K = \frac{[NOBr]^2}{[NO]^2[Br_2]}$$

b. $$Q = \frac{(10.0 \text{ M})^2}{(10.0 \text{ M})^2 \times 5.0 \text{ M}}$$

$Q = 0.20 \text{ M}^{-1}$ (1 MARK)

Therefore, $Q > K$, and Q will decrease as the system approaches equilibrium. (1 MARK)

Hence, the reaction will proceed in the reverse direction as the production of more reactants will result in the lowering of Q. (1 MARK)

c. i. Fatal or toxic if swallowed, inhaled or in contact with skin

ii. Wearing respiratory protection (face-mask)

Alternative answer:

- Conducting the investigation in a fume cupboard

d. [One chemist citing 'shortness of breath' is simply anecdotal,[1]][and it is not sufficiently indicative of a substance's ability to cause respiratory problems.[2]]

✓ ✗ I have identified the chemist's shortness of breath as anecdotal evidence.[1]

✓ ✗ I have explained that anecdotal evidence is not sufficient to make scientific conclusions.[2]

FROM LESSONS 12A & 12B

Questions from multiple lessons

17. A. For the reaction $\frac{1}{3}N_2(g) + H_2(g) \rightleftharpoons \frac{2}{3}NH_3(g)$,

$\Delta H = \frac{1}{3} \times -92.3 \text{ kJ}$

$\Delta H = -30.8 \text{ kJ}$

and

$K = (640)^{\frac{1}{3}}$

$K = 8.6$

$K \approx 9 \text{ (M}^{-2})$

Note: The 'magnitude' refers to a numerical value and does not require units.

FROM LESSON 1D

18. D. Since there is an equal number of moles of gas particles on both sides of the equation, the volume of the container does not affect the ratio of [products] to [reactants]. Hence,

$$K = \frac{[HF]}{[H_2]^{\frac{1}{2}}[F_2]^{\frac{1}{2}}}$$

$$K = \frac{(n(HF)/V)}{(n(H_2)/V)^{\frac{1}{2}} \times (n(F_2)/V)^{\frac{1}{2}}}$$

$$K = \frac{(n(HF)/V)}{(n(H_2)^{\frac{1}{2}}/V^{\frac{1}{2}}) \times (n(F_2)^{\frac{1}{2}}/V^{\frac{1}{2}})}$$

$$K = \frac{(n(HF)/V)}{(n(H_2)^{\frac{1}{2}} \times n(F_2)^{\frac{1}{2}})/V}$$

$$K = \frac{n(HF)}{(n(H_2)^{\frac{1}{2}} \times n(F_2)^{\frac{1}{2}}}$$

19. B. Energy released during the production of 0.220 mol of HF = 0.220 mol × 271 kJ per mol HF

Energy released during the production of 0.220 mol of HF = 59.6 kJ

Therefore, the heat exchanger must absorb 59.6 kJ of heat energy.

FROM LESSON 2A

5C Changes to equilibrium

Progress questions

1. D. Le Chatelier's principle is used to predict the change in the position of equilibrium, and hence the changes in the concentrations of reactants and products when a stress is applied to a system.

2. C. By Le Chatelier's principle, the system will shift to partially oppose the decrease in concentration of the products by forming more products. Hence, the system will shift to the right, favouring the forward reaction (formation of products).

3. A. The graph shows an immediate spike in only the [X(aq)] at t_1, indicating that X(aq) has been added to the equilibrium system.

4. B. According to Le Chatelier's principle, when an increase in pressure is applied to a system in equilibrium, the system will move to partially oppose this increase by favouring the reaction that produces fewer gas particles until equilibrium is re-established.

5. A. From the graph, we can see an instantaneous decrease in the concentration of all species, which occurs when the volume of the reaction vessel is increased at a constant temperature.

6. C. The addition of an inert (unreactive) gas to a reaction vessel has no effect on the position of equilibrium.

7. A. When the temperature is increased, the endothermic reaction is favoured. Since the forward reaction is endothermic in this case, the system will shift to the right, resulting in an increase in the value of *K*.

8. B. An increase in temperature will increase the rate of the forward reaction. Since the reaction is exothermic, an increase in temperature will favour the reverse reaction according to Le Chatelier's principle, and thus, the $[NH_3]$ will decrease.

Deconstructed

9. B **10.** C

11. C. The change in the rate of the reverse reaction at time t_1 is consistent with the addition of products. By Le Chatelier's principle, the system will partially oppose this change by favouring the forward reaction, resulting in a greater amount of products at time t_2 than at time t_1.

Exam-style

12. [The value of the equilibrium constant will decrease.[1]][Since the forward reaction is exothermic,[2]][the increase in temperature will cause the system to partially oppose this change by shifting in favour of the reverse reaction to absorb the increased heat energy, as per Le Chatelier's principle.[3]][Since the reverse reaction is favoured, the [reactants] will increase and the [products] will decrease, causing the value of *K* to decrease.[4]]

✓ ✗ I have stated that the equilibrium constant will decrease.[1]

✓ ✗ I have identified that the forward reaction is exothermic.[2]

✓ ✗ I have explained the the effect of the temperature increase on the position of equilibrium.[3]

✓ ✗ I have identified that the [reactants] will increase and the [products] will decrease.[4]

13. D. In solution, NaOH dissociates into Na^+ and OH^-. The added OH^- will react with H^+, in turn removing H^+ from the system. To partially oppose this decrease in $[H^+]$, the system will shift to the left, favouring the reverse reaction. This will result in an increased concentration of CrO_4^{2-}.

14. B. To increase the $[H_3O^+]$, the second equilibrium must move to the right. By bubbling more $CO_2(g)$ into the system, the concentration of $CO_2(aq)$ will increase. In turn, the system will move to partially oppose this change by favouring the forward reaction of the first equilibrium, thereby increasing the $[H_2CO_3]$. As a result, the second equilibrium will move to partially oppose the increase in the $[H_2CO_3]$ by favouring the forward reaction, ultimately increasing the $[H_3O^+]$.

15. A. The gradual adjustment to the change at 1 minute is consistent with a change in temperature. Since the reverse endothermic reaction is favoured, the temperature was increased. The sudden and proportional decrease in all concentrations at 7 minutes is consistent with a volume increase to which the system responds by favouring the reverse reaction to partially compensate for the imposed decrease in pressure.

16. a. i. [The yield of methanol is greater at low temperatures.[1]][The forward reaction is exothermic, so according to Le Chatelier's principle, if the temperature is lowered the system will move to raise the temperature (partially compensate) by favouring the exothermic forward reaction.[2]]

✓ ✗ I have identified the effect of reaction temperature on the yield of methanol.[1]

✓ ✗ I have explained this effect using Le Chatelier's principle.[2]

ii. [The yield of methanol is greater at high pressure.[1]][According to Le Chatelier's principle, at high pressure, the system moves to decrease pressure by favouring the reaction that produces fewer particles in a given volume, which in this case is the forward reaction (3 mol → 1 mol), thus increasing the yield of methanol.[2]]

✓ ✗ I have identified the effect of reaction pressure on the yield of methanol.[1]

✓ ✗ I have explained this effect using Le Chatelier's principle.[2]

b. $K = \dfrac{[CH_3OH]}{[CO][H_2]^2}$

c.

Amt. (mol)	$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g)$		
n	1	2	1
I	0.760	0.525	0
C	−0.122	$-(2 \times 0.122)$	+0.122 (1 MARK)
E	$0.760 - 0.122 = 0.638$	$0.525 - (2 \times 0.122) = 0.281$	0.122
Conc. (M)	$c(CO) = \frac{n}{V}$ $c(CO) = \frac{0.638 \text{ mol}}{0.500 \text{ L}}$ $c(CO) = 1.276 \text{ M}$	$c(H_2) = \frac{n}{V}$ $c(H_2) = \frac{0.281 \text{ mol}}{0.500 \text{ L}}$ $c(H_2) = 0.562 \text{ M}$	$c(CH_3OH) = \frac{n}{V}$ $c(CH_3OH) = \frac{0.122 \text{ mol}}{0.500 \text{ L}}$ $c(CH_3OH) = 0.244 \text{ M}$ (1 MARK)

$$K = \frac{[CH_3OH]}{[CO][H_2]^2}$$

$$K = \frac{0.244 \text{ M}}{1.276 \text{ M} \times (0.562 \text{ M})^2}$$

$K = 0.605 \text{ M}^{-2}$ (3 sig. figs) (1 MARK)

17. [When added to the solution, NaHS will dissolve, causing an increase in the $[HS^-]$. According to Le Chatelier's principle, the equilibrium of reaction (1) will move to partially oppose this change by shifting to the left, favouring the reverse reaction to remove the added $HS^-(aq)$.[1]][Since H_3O^+ is a reactant of the reverse reaction and is therefore used up when the reverse reaction is favoured, the pH of the solution will increase due to the decreased $[H_3O^+]$.[2]]

✓ ✗ I have explained the effect of adding NaHS on the position of equilibrium.[1]

✓ ✗ I have linked my answer to the question.[2]

Key science skills

18. a.

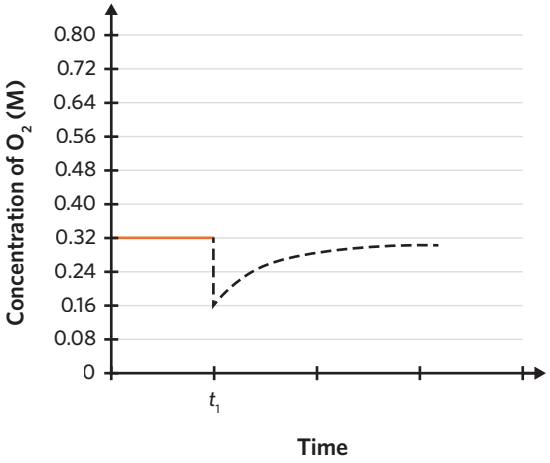
Conc.	$O_2(g) + 2SO_2(g) \rightleftharpoons 2SO_3(g)$		
n	1	2	2
I	$c(O_2) = \frac{n}{V}$ $c(O_2) = \frac{5.0 \text{ mol}}{5.0 \text{ L}}$ $c(O_2) = 1.0 \text{ M}$	$c(SO_2) = \frac{n}{V}$ $c(SO_2) = \frac{10.0 \text{ mol}}{5.0 \text{ L}}$ $c(SO_2) = 2.0 \text{ M}$	0 M
C	−0.68 M	$-(2 \times 0.68 \text{ M})$	$+(2 \times 0.68 \text{ M})$
E	$1.0 \text{ M} - 0.68 \text{ M} = 0.32 \text{ M}$	$2.0 \text{ M} - (2 \times 0.68 \text{ M}) = 0.64 \text{ M}$	1.36 M (1 MARK)

$$K = \frac{[SO_3]^2}{[O_2][SO_2]^2} \quad \text{(1 MARK)}$$

$$K = \frac{(1.36 \text{ M})^2}{0.32 \text{ M} \times (0.64 \text{ M})^2}$$

$K = 14 \text{ M}^{-1}$ (2 sig. figs) (1 MARK)

b. i.



✓ ✗ I have drawn a graph indicating that the $[O_2]$ halves to 0.16 M at time t_1.[1]

✓ ✗ I have drawn a graph indicating that the $[O_2]$ increases (does not reach 0.32) following the change at time t_1 until equilibrium is re-established.[2]

ii. [Since the volume of the reaction vessel is doubled from 5.0 L to 10.0 L at time t_1, the $[O_2]$ halves from 0.32 M to 0.16 M, as per the equation $c = \frac{n}{V}$.[1]][According to Le Chatelier's principle, when the system is diluted, the system will move to partially oppose this change by favouring the reaction that produces more particles, that being the reverse reaction. Since O_2 is a product of the reverse reaction, the $[O_2]$ gradually increases until equilibrium is re-established.[2]]

✓ ✗ I have explained the instantaneous decrease in the $[O_2]$ at time t_1.[1]

✓ ✗ I have explained the gradual increase in the $[O_2]$ after time t_1.[2]

c. i. [Since the formation of sulfur trioxide (the forward reaction) is exothermic, the yield of sulfur trioxide will be increased under lower temperatures, due to favouring of the exothermic forward reaction.[1]][Additionally, since the reaction that produces sulfur trioxide also produces the fewest moles of gas, the yield of sulfur trioxide will be increased under higher pressures.[2]][As Company 2 uses both a low temperature and high pressure, they will generate the highest percentage yield of sulfur trioxide, albeit at a slower rate.[3]]

✓ ✗ I have explained that the formation of sulfur trioxide is favoured by lower temperatures.[1]

✓ ✗ I have explained that the formation of sulfur trioxide is favoured by higher pressures.[2]

✓ ✗ I have linked my answer to the question.[3]

ii. Using high pressure and temperature results in higher expenses due to both the cost of maintaining higher energy conditions and the cost of the equipment needed to withstand these higher energy conditions.

iii. Sulfur dioxide, a reactant in this step of the process, is a pollutant that can contribute to the formation of acid rain by reacting with water in the atmosphere.

FROM LESSONS 12B, 12C & 12E

Questions from multiple lessons

19. a.

Change to reaction 1 and 2	Effect of the change on the yield of H_2	
	Reaction 1	Reaction 2
Addition of steam at a constant volume and temperature	Increase	Increase (1 MARK)
Increase in temperature at a constant volume	Increase	Decrease (1 MARK)
Addition of a suitable catalyst at a constant volume and temperature	No change	No change (1 MARK)

b. i. [Decreasing the volume increases the overall pressure (or concentration of gases). The system moves to partially oppose this change and decrease the pressure (or concentration) by favouring the side with fewer particles, which for reaction 1 is the reverse reaction.[1]] [Since the reverse reaction is favoured, the equilibrium yield of hydrogen will be lower.[2]]

✓ ✗ I have explained the effect of decreasing volume on the position of equilibrium for reaction 1.[1]

✓ ✗ I have linked my answer to the question.[2]

ii. [Although the pressure increases, the system cannot respond to a pressure increase because there are the same number of particles on both sides of the equation for reaction 2.[1]] [Hence, the equilibrium yield of hydrogen does not change.[2]]

✓ ✗ I have explained the effect of decreasing volume on the position of equilibrium for reaction 2.[1]

✓ ✗ I have linked my answer to the question.[2]

c. i. The rate of hydrogen production will increase due to an increase in the kinetic energy of the reaction.

ii. The rate of hydrogen production will increase due to an increase in the kinetic energy of the reaction.

d. i. $O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$

ii. $H_2(g) + 2OH^-(aq) \rightarrow 2H_2O(l) + 2e^-$

e. $E^0 = +0.40\ V - (-0.83\ V)$

$E^0 = +1.23\ V$

f. [Methane produced from plant material (biomass) can be readily replenished in a short period of time, meaning it can be produced as (or more) quickly as it is consumed, making it renewable.[1]] [Methane produced from natural gas, a fossil fuel which takes millions of years to form, cannot be produced more quickly than it is consumed, and is thus non-renewable.[2]]

✓ ✗ I have explained why methane produced from biomass is renewable.[1]

✓ ✗ I have explained why methane produced from natural gas is non–renewable.[2]

FROM LESSONS 1B, 3D, 3E & 4A

5D Compromise conditions

Progress questions

1. C. According to the graph, the yield of Y is favoured at higher temperatures and lower pressures. The reaction that produces Y must therefore produce more moles of gas, and must be endothermic, which aligns with option C.

2. C. Catalysts can increase the rate of reactions at lower temperatures. A catalysed reaction produces the same amount of product as an uncatalysed reaction but it produces the product at a faster rate. The yield is unchanged but the rate of production is increased.

3. D. When the temperature of a reaction vessel is higher, the risk of unwanted side reactions increases.

4. A. Using a catalyst will increase the rate of formation of methanol by lowering the activation energy required for the reaction.

5. B. Heat exchangers can reuse heat that would otherwise be lost to the environment.

6. C. Using renewable energy sources like solar panels reduces the amount of CO_2 released into the atmosphere that occurs from burning fossil fuels.

Deconstructed

7. D **8.** B

9. a. [Since the forward reaction is exothermic, the reverse reaction is endothermic. By Le Chatelier's principle, at higher temperatures, the endothermic direction of an equilibrium reaction is favoured as the system attempts to partially absorb the increased heat energy.[1]] [Hence, the reverse reaction will be favoured, causing a lower yield of sulfur trioxide.[2]]

✓ ✗ I have explained the direction referring to Le Chatelier's principle.[1]

✓ ✗ I have justified why the reverse reaction is favoured.[2]

b. If the temperature is too low, then the rate of sulfur trioxide formation is too low which is not economically viable.

Exam-style

10. a. II – Since the forward reaction is favoured at higher temperatures and lower pressures, the reverse reaction – which yields A(g) – is favoured at lower temperatures and higher pressures.

b. IV – The temperature of 300 °C combined with the pressure of 200 kPa would provide the fastest rate of reaction, as the proportion of particles that collide will be greater (due to high pressure and temperature), and the proportion of particles that collide successfully will also be greater (due to high temperature).

11. a. 600 K, 40 MPa

b. First, we need to calculate the percentage yield of wallacium for each factory.

Factory 1:

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}}$$

$$\% \text{ yield} = \frac{3000 \text{ kg}}{6000 \text{ kg}} \times 100\%$$

$$\% \text{ yield} = 50\% \quad (1 \text{ MARK})$$

Factory 2:

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}}$$

$$\% \text{ yield} = \frac{12 \times 150 \text{ kg}}{6000 \text{ kg}} \times 100\%$$

$$\% \text{ yield} = 30\% \quad (1 \text{ MARK})$$

From the graph, the factory that has a 50% yield of wallacium operates at 700 K, whilst the factory that has a 30% yield of wallacium operates at 800 K. Therefore, Factory 1 operates at 700 K and Factory 2 operates at 800 K. (1 MARK)

c. [Factory 1 achieves a greater percentage yield of wallacium than Factory 2.[1]][Factory 1 also uses a lower temperature than Factory 2 to yield more wallacium, making its production more energy efficient.[2]][However, Factory 2 produces 150 kg of wallacium per hour compared to Factory 1's 125 kg of wallacium per hour.[3]][In turn, Factory 2's production method is more economically viable as the labour costs are halved (12 hours vs 24 hours) and the wallacium is produced at a faster hourly rate.[4]][Ultimately, despite Factory 1 obtaining a greater percentage yield of wallacium, the conditions of Factory 2 are more balanced with respect to the compromise between rate of production and yield.[5]]

- ✓ ✗ I have identified which factory has a greater percentage yield of wallacium.[1]
- ✓ ✗ I have explained that Factory 1 has a more energy efficient production method.[2]
- ✓ ✗ I have identified which factory produces wallacium at a faster hourly rate.[3]
- ✓ ✗ I have explained that Factory 2 has a more economically viable production method.[4]
- ✓ ✗ I have identified which factory is more balanced with respect to the compromise between rate and yield.[5]

Key science skills

12. a. 10% Cs–FePc

b. The most suitable combination of pressure, temperature and catalyst to optimise the yield of ammonia is

- High pressure
- Low temperature
- 10% Cs–FePc catalyst

c. [Despite being favoured at lower temperatures, the rate of ammonia production would be too low.[1]][Instead, chemists use compromise conditions of high pressure and high temperature in order to increase the rate of production, which offsets the decrease in yield.[2]]

- ✓ ✗ I have explained that the rate of ammonia production is low at lower temperatures.[1]
- ✓ ✗ I have described the benefit of using compromise conditions.[2]

d. The Fe–benchmark catalyst serves as a control to compare the other catalysts against.

e. [The CO_2 emissions from the steam methane reforming process contribute to the greenhouse effect,[1]][which in turn causes global warming.[2]]

- ✓ ✗ I have identified that CO_2 emissions contribute to the greenhouse effect.[1]
- ✓ ✗ I have explained that the greenhouse effect causes global warming.[2]

f. [The key ingredient in fertiliser is ammonia, and so the main requirement for fertiliser production is the availability of reactants (hydrogen and nitrogen), as well as general needs such as labour, access to markets, and the safe management of waste.[1]][Since nitrogen gas is abundant in the atmosphere, both sites have a readily available source of nitrogen. Additionally, both sites have relatively easy access to sources of hydrogen gas; site A has a nearby steam methane reforming plant and site B has a nearby water electrolysis plant.[2]] [However, since steam methane reforming requires the use of fossil fuels and gives off significantly greater CO_2 emissions than the electrolysis of water, site B's source of hydrogen is more sustainable and environmentally friendly. Additionally, site B is nearer to the wind farm, meaning it has easier access to a sustainable source of energy.[3]][Whilst site B has better options for sustainable production, site A is more logistically viable as its railway line is significantly closer to the Port City, which would have facilities to ship fertiliser to markets.[4]] [Site A, however, is also closer to the ocean. This results in a greater likelihood of waste running off into the ocean, potentially damaging marine life. Site B, on the contrary, does not appear to be close to any bodies of water, meaning waste can be managed more easily.[5]][Hence, site B enables more environmentally conscious production of fertiliser and should therefore be the preferred location for the plant.[6]]

- ✓ ✗ I have identified the main requirements for a fertiliser plant.[1]
- ✓ ✗ I have evaluated the availability of reactants for each site.[2]
- ✓ ✗ I have evaluated the sustainability of the sources of reactants and energy for each site.[3]
- ✓ ✗ I have evaluated the shipping logistics of each site.[4]

I have explained concerns around waste management for each site.[5]

I have linked my answer to the question.[6]

FROM LESSONS 12A, 12B, 12C & 12E

Questions from multiple lessons

13. [The combustion of fossil fuels releases CO_2 and heat into the atmosphere, as per the following equation for the combustion of methane (for example): $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$.[1]] [Therefore, increased burning of fossil fuels will contribute to further rises in the level of atmospheric CO_2.[2]] [This atmospheric CO_2 will absorb heat energy emitted from the Earth, causing the temperature of the air to rise.[3]] [Much of the heat energy in the air is transferred into oceans, causing their temperatures to rise too.[4]] [The following equations represent the equilibrium formed when atmospheric CO_2 reacts with water in the ocean:
$CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$
$H_2CO_3(aq) \rightleftharpoons H^+(aq) + HCO_3^-(aq)$
$HCO_3^-(aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$.[5]]
[According to Le Chatelier's principle, as the amount of atmospheric CO_2 increases, the concentration will increase in the atmosphere. As a result, the ocean absorbs more CO_2 to oppose this increase in concentration, causing an increased concentration of carbon dioxide dissolved in the ocean.[6]]

I have identified that CO_2 is released from the combustion of fossil fuels.[1]

I have linked the increase in fossil fuel burning to the increase in atmospheric CO_2.[2]

I have explained the effect of increased atmospheric CO_2 on the temperature of the air.[3]

I have explained the effect of increased air temperature on ocean temperature.[4]

I have identified the equilibrium formed between CO_2 and water.[5]

I have used Le Chatelier's principle to explain the effect of increased atmospheric CO_2 on the concentration of carbon dioxide dissolved in the oceans.[6]

FROM LESSONS 1A, 1D & 5C

Chapter 5 review

Multiple choice

1. B. The equilibrium constant is only affected by changes in temperature.

2. B. Statement I is incorrect as whilst the concentrations of the reactants and products at equilibrium are constant, they are not necessarily equal. Statement II is incorrect as at equilibrium, there is always some amount of both reactants and products present. At equilibrium, the rates of the forward and reverse reactions are equal, so statement III is correct.

3. A. The reverse reaction is $CO_2(g) + 4H_2(g) \rightleftharpoons 2H_2O(g) + CH_4(g)$, which gives the expression $K = \frac{[H_2O]^2[CH_4]}{[H_2]^4[CO_2]}$.

4. D. Since all concentrations increased at time t_2, the volume of the system was decreased.

5. A. The temperature decrease causes the rate of both the forward and reverse reactions to decrease. To return to equilibrium, the forward reaction is favoured so the $[SO_2Cl_2]$ increases. Hence, the $[SO_2Cl_2]$ will be greater at time t_4 than at time t_3.

6. A.

Amount (mol)	$I^-(aq)$	+ $I_2(aq)$	⇌ $I_3^-(aq)$
n ratio	1	1	1
Initial	0	0	0.60
Change	+0.18	+0.18	−0.18
Equilibrium	0.18	0.18	0.42

$c(I^-) = \frac{n}{V}$

$c(I^-) = \frac{0.18 \text{ mol}}{2.00 \text{ L}}$

$c(I^-) = 0.09 \text{ M}$

$c(I_2) = \frac{n}{V}$

$c(I_2) = \frac{0.18 \text{ mol}}{2.00 \text{ L}}$

$c(I_2) = 0.09 \text{ M}$

7. A. The rate-time graph provided indicates that the rate of the forward reaction increased because of the change imposed at t_1, which aligns with an increase in temperature. Since the forward reaction is exothermic, the temperature increase will favour the endothermic reverse reaction. Hence, the position of equilibrium shifts to the left and as the [HI] increases, the colour of the mixture will lighten.

8. D. Since the concentrations of all species double, but the amounts of each species remain unchanged, the volume of the system is halved at time t_2. Hence, the position of equilibrium has not changed, and the system is still in equilibrium at time t_3. Therefore, the forward and reverse reactions are occurring at the same rate. Given the forward reaction produces 1 mol of HI and the reverse reaction produces $\frac{1}{2}$ mol of H_2, the rate of production of HI at time t_3 is double the rate of production of H_2 at time t_3.

9. A. Since the equilibrium constant has been altered, a change in temperature must have occurred. Additionally, since the rate of the reverse reaction (and hence also the forward reaction) at time t_5 was higher than at time t_3, the temperature must have been increased. Since the forward reaction is endothermic, the forward reaction is favoured by the increase of temperature, causing the total chemical energy of the system to increase.

10. D.

Amount (mol)	$2NO(g)$	+ $O_2(g)$	⇌ $2NO_2(g)$
n ratio	2	1	2
Initial	0	0	4.0
Change	+1.5	+0.75	−1.5
Equilibrium	1.5	0.75	2.5

At equilibrium:

$c(NO) = \frac{n}{V}$

$c(NO) = \frac{1.5 \text{ mol}}{3.0 \text{ L}}$

$c(NO) = 0.50\ M$

$c(O_2) = \frac{n}{V}$

$c(O_2) = \frac{0.75\ mol}{3.0\ L}$

$c(O_2) = 0.25\ M$

$c(NO_2) = \frac{n}{V}$

$c(NO_2) = \frac{2.5\ mol}{3.0\ L}$

$c(NO_2) = 0.833\ M$

$K = \frac{[NO_2]^2}{[NO]^2[O_2]}$

$K = \frac{(0.833\ M)^2}{(0.50\ M)^2 \times 0.25\ M}$

$K = 11\ M^{-1}$

Short answer

11. a. $K = \frac{[CoCl_4^{2-}]}{[[Co(H_2O)_6]^{2+}][Cl^-]^4}$

b. [The dilution decreases the concentration of all ions. Per Le Chatelier's principle, to partially oppose this change, this system will favour the reverse reaction since there are more ions on the reactants side of the equation.[1]] [Consequently, after the initial change to a lighter blue (due to a decrease in the $[CoCl_4^{2-}]$), the colour will become a deeper pink as the $[Co(H_2O)_6^{2+}]$ increases.[2]]

- I have used Le Chatelier's principle to explain in which direction the system will shift.[1]
- I have explained the resultant colour change of the solution.[2]

c. [Since the solution is pink at 4 °C and blue at 25 °C, the forward reaction must be favoured as the temperature increases.[1]] [This indicates that forward reaction is endothermic.[2]]

- I have explained that the forward reaction is favoured by increasing temperature.[1]
- I have identified that the forward reaction is endothermic.[2]

d. $Q = \frac{[CoCl_4^{2-}]}{[[Co(H_2O)_6]^{2+}][Cl^-]^4}$

$Q = \frac{0.030\ M}{2.0\ M \times (4.2\ M)^4}$

$Q = 4.8 \times 10^{-5}\ M^{-4}$ (1 MARK)

Since $Q > K$, the system is not at equilibrium. (1 MARK)

12. a. [Given the forward reaction is exothermic ($\Delta H < 0$), by Le Chatelier's principle, the reverse reaction will be favoured by the higher temperature of the water in the beaker.[1]] [Since the reverse reaction is favoured, the $[NO_2]$ will increase,[2]] [causing the gas mixture to become a darker brown.[3]]

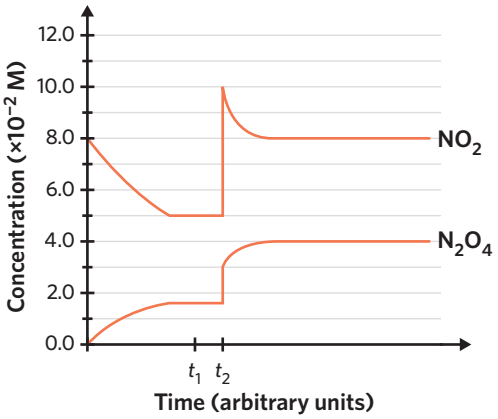
- I have identified that the reverse reaction is exothermic and is therefore favoured at the higher temperature.[1]
- I have explained that the $[NO_2]$ will increase.[2]
- I have identified the colour change that would occur.[3]

b. i. $K = \frac{[N_2O_4]}{[NO_2]^2}$

$K = \frac{1.5 \times 10^{-2}\ M}{(5.0 \times 10^{-2}\ M)^2}$ (1 MARK)

$K = 6.0\ M^{-1}$ (1 MARK)

ii.



- I have shown that the $[NO_2]$ and $[N_2O_4]$ both doubled at time t_2.[1]
- I have subsequently shown that the $[NO_2]$ decreases and the $[N_2O_4]$ increases.[2]
- I have shown that change in $[NO_2]$ is double the magnitude of that of N_2O_4 as the system re-establishes equilibrium.[3]

13. a. [According to Le Chatelier's principle, as the temperature increases, the endothermic (energy–absorbing) reaction is favoured in order to partially oppose the addition of heat energy.[1]] [From Graph 1, the $[O_3]$ increases as the temperature increases, meaning the forward reaction is favoured.[2]] [Therefore, the forward reaction is endothermic.[3]]

- I have used Le Chatelier's principle to explain which reaction is favoured by an increase in temperature.[1]
- I have used Graph 1 to determine which reaction direction is favoured.[2]
- I have identified that the forward reaction is endothermic.[3]

b.

Amount (mol)	$3O_2(g)$	⇌	$2O_3(g)$
n ratio	3		2
Initial	7.50×10^{-2}		0
Change	$-\left(\frac{3}{2} \times 1.56 \times 10^{-7}\right)$ (1 MARK)		$+1.56 \times 10^{-7}$
Equilibrium	0.0749998		1.56×10^{-7}

$c(O_2) = \frac{n}{V}$

$c(O_2) = \frac{0.07499 \text{ mol}}{3.00 \text{ L}}$

$c(O_2) = 0.0250 \text{ M}$

$c(O_3) = \frac{n}{V}$

$c(O_3) = \frac{1.56 \times 10^{-7} \text{ mol}}{3.00 \text{ L}}$

$c(O_3) = 5.20 \times 10^{-8} \text{ M}$ (1 MARK)

$K = \frac{[O_3]^2}{[O_2]^3}$

$K = \frac{(5.20 \times 10^{-8} \text{ M})^2}{(0.0250 \text{ M})^3}$ (1 MARK)

$K = 1.73 \times 10^{-10} \text{ M}^{-1}$ (1 MARK)

14. a. [Experiment 2 has a higher initial concentration of NOCl molecules, so there will be a higher frequency of collisions (higher number of collisions per unit time) and so a higher frequency of successful collisions (higher number of successful collisions per unit time) between NOCl molecules.[1]][Hence, Experiment 2 has the higher initial rate of Cl_2 production.[2]]

✓ ✗ I have described the effect of [NOCl] on the frequency of successful collisions.[1]

✓ ✗ I have explained that Experiment 2 has the higher initial rate of Cl_2 production.[2]

b. [Experiment 2 is equivalent to adding 2 mol of NOCl to the container in Experiment 1 once it reaches equilibrium. Hence, by Le Chatelier's principle, the system will partially oppose the addition of NOCl by favouring the reverse reaction. As a result, the $[Cl_2]$ at equilibrium in Experiment 2 will be higher. Since the value of K must be equal in both Experiment 1 and 2, the higher $[Cl_2]$ at equilibrium in Experiment 2 requires an increase in the ratio $\frac{[NOCl]^2}{[NO]^2}$.[1]][For the ratio to increase, the [NOCl] must be greater than [NO] at equilibrium in Experiment 2.[2]]

✓ ✗ I have explained the relationship between the ratios of products and reactants in each experiment at equilibrium.[1]

✓ ✗ I have identified that the [NOCl] > [NO] at equilibrium in Experiment 2.[2]

c. [Whilst there are more collisions occurring per unit time due to the added particles, the frequency of successful collisions does not change since collisions involving inert gas particles do not affect equilibrium.[1]][Hence, the rate of Cl_2 production in Experiment 1 will not change.[2]]

✓ ✗ I have explained the effect of inert gases on the frequency of successful collisions.[1]

✓ ✗ I have linked this explanation to the rate of Cl_2 production.

d. [Since the forward reaction is endothermic, according to Le Chatelier's principle the system will partially oppose the increase in temperature by favouring the endothermic (energy-absorbing) reaction.[1]][Hence, the [NOCl] will increase.[2]]

✓ ✗ I have used Le Chatelier's principle to explain the effect of a temperature increase on the system.[1]

✓ ✗ I have identified that the [NOCl] will increase.[2]

Key science skills

15. a. $K = \frac{[SCN^-][Fe^{3+}]}{[FeSCN^{2+}]}$

b. Unit $= \frac{\text{M} \times \text{M}}{\text{M}}$

Unit = M

c. 1 mark per two correct ticks
Less red: I; III; IV
More red: II

FROM LESSONS 12A & 12C

16. a. [Manufacturers will often alter reaction conditions to increase the rate of production, despite providing a lower percentage yield.[1]][This is done to determine which combination of temperature and pressure maintains a sufficient rate and yield whilst saving on costs.[2]]

✓ ✗ I have identified the compromise made.[1]

✓ ✗ I have explained the compromise in terms of financial considerations.[2]

Alternative answer:

- Manufacturers will moderate the temperatures and pressures used in the reaction systems. By using less extreme temperatures and pressures, the energy costs are reduced.

b. [Manufacturers may use lower temperatures and catalysts to maintain a sufficient reaction rate and lower the energy input required,[1]][thereby reducing the amount of fossil fuels (the major energy source in most chemical processes) consumed.[2]]

✓ ✗ I have identified the compromise made.[1]

✓ ✗ I have explained the compromise in terms of energy and environmental considerations.[2]

Alternative answer:

- Manufacturers will moderate the temperatures and pressures used in the reaction systems. By using less extreme temperatures and pressures, the amount of energy used – and therefore the amount of fossil fuels consumed – is reduced.

c. [Manufacturers will moderate the temperatures and pressures used in the reaction systems.[1]][By using less extreme temperatures and pressures, the risk of explosions is reduced.[2]]

✓ ✗ I have identified the compromise made.[1]

✓ ✗ I have explained the compromise in terms of health and safety considerations.[2]

FROM LESSONS 12B & 12E

6A Electrolytic reactions

Progress questions

1. B. Electrolytic reactions convert electrical energy into chemical energy.

2. C. Electrolytic reactions require an external power source to provide a voltage over a certain threshold to be feasible.

3. B. In order for these two half-equations to be added together to form the overall redox equation, the coefficients of the reduction half-equation must be doubled so that each equation has the same number of electrons and the same charge of +2 on each side.

4. C. Equations B and D represent oxidation reactions, as electrons are only present in the products and are shown to be lost by HSO_3^-. Equation A is unbalanced.

5. B. The electrochemical series can help identify the strongest oxidising agent and the strongest reducing agent present, as well as both the oxidation and reduction electrolytic half-equations when the voltage input and concentrations of any potential aqueous reactants are known.

Deconstructed

6. A

7. B

8. A. $K^+(aq)$, $SO_4^{2-}(aq)$, and $H_2O(l)$ are initially present.

The strongest oxidising agent present (top left) is predicted to react with the strongest reducing agent present (bottom right). Species available to react are highlighted in blue and red.

$S_2O_8^{2-}(aq) + 2e^- \rightleftharpoons 2SO_4^{2-}(aq)$ $\quad E^0 = +2.01\ V$

$O_2(g) + 4H^+(aq) + 4e^- \leftarrow 2H_2O(l)$ $\quad E^0 = +1.23\ V$

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$ $\quad E^0 = -0.83\ V$

$K^+(aq) + e^- \rightleftharpoons K(s)$ $\quad E^0 = -2.93\ V$

Reduction half-reaction: $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

Oxidation half-reaction: $2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

The reduction half-equation must be doubled before these equations can be added together to form the overall redox equation so that both equations contain the same number of electrons.

The unsimplified overall reaction is

$6H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 2H_2(g) + 4OH^-(aq)$

As $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$, this reaction can be simplified to become

$6H_2O(l) \rightarrow O_2(g) + 2H_2(g) + 4H_2O(l)$

Water molecules that appear on both sides of the equation can be cancelled to form the balanced overall redox equation.

$2H_2O(l) \rightarrow O_2(g) + 2H_2(g)$

Exam-style

9. C. An electrolytic reaction can be thought of as the reverse reaction of a feasible spontaneous redox reaction.

10. D. For Mg(s) to be produced, Mg^{2+} ions must be reduced.

$I_2(s) + 2e^- \leftarrow 2I^-(aq)$

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$

However, for $MgI_2(aq)$ the electrochemical series indicates that an aqueous solution cannot be used because H_2O is a stronger oxidising agent (top left) than $Mg^{2+}(aq)$ and would be preferentially reduced.

11. a. [Zoran's statement is incorrect because an electrolytic reaction will only occur given a sufficient voltage.[1]][Therefore, if a sufficient voltage is not applied for the electrolysis reaction between Pb(s) and $Ni^{2+}(aq)$, no reaction will occur, which explains why no changes are observed.[2]]

✓ ✗ I have evaluated the accuracy of Zoran's statement.[1]

✓ ✗ I have explained Zoran's experimental results.[2]

b. [Oxidation: $Pb(s) \rightarrow 2e^- + Pb^{2+}(aq)$[1]]
[Reduction: $Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$[2]]

✓ ✗ I have balanced the oxidation half-equation.[1]

✓ ✗ I have balanced the reduction half-equation.[2]

12. a. $Pb^{2+}(aq) + 2H_2O(l) \rightarrow PbO_2(s) + 4H^+(aq) + 2e^-$

b. $Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$

c. $2Pb^{2+}(aq) + 2H_2O(l) \rightarrow Pb(s) + PbO_2(s) + 4H^+(aq)$

13. a. [Oxidation: $Fe(l) \rightarrow 3e^- + Fe^{3+}(l)$[1]]
[Reduction: $Mg^{2+}(l) + 2e^- \rightarrow Mg(l)$[2]]

✓ ✗ I have balanced the oxidation half-equation.[1]

✓ ✗ I have balanced the reduction half-equation.[2]

b. $2Fe(l) + 3Mg^{2+}(l) \rightarrow 2Fe^{3+}(l) + 3Mg(l)$

14. [The student's prediction is inaccurate.[1]][According to the electrochemical series, $Cu^{2+}(aq)$ is a stronger oxidising agent than $Co^{2+}(aq)$, which means that $Cu^{2+}(aq)$ will be reduced in preference to $Co^{2+}(aq)$.[2]]

✓ ✗ I have identified whether the student's prediction is accurate.[1]

✓ ✗ I have used the electrochemical series to justify my answer.[2]

Key science skills

15. a. [Hydrogen gas, $H_2(g)$, is produced at the cathode,[1]]
[and oxygen gas, $O_2(g)$, is produced at the anode.[2]]
[Reduction: $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$[3]]
[Oxidation: $2H_2O(l) \rightarrow O_2(g) + 2H^+(aq) + 4e^-$[4]]

- ✓ ✗ I have identified one gas that is produced.[1]
- ✓ ✗ I have identified the second gas that is produced.[2]
- ✓ ✗ I have correctly balanced and included states for the reduction reaction.[3]
- ✓ ✗ I have correctly balanced and included states for the oxidation reaction.[4]

b. i. Hydrogen gas, $H_2(g)$, is highly flammable and very explosive in the presence of oxygen gas.

ii. This reaction should occur away from an open flame and in a well-ventilated area/fume hood.

c. i. Chlorine gas is poisonous when inhaled.

ii. This reaction should occur in a well ventilated area/ fume hood.

FROM LESSON 12B

Questions from multiple lessons

16. a. [Oxidation: $Ni(s) \rightarrow 2e^- + Ni^{2+}(aq)$[1]]
[Reduction: $Ag^+(aq) + e^- \rightarrow Ag(s)$[2]]

- ✓ ✗ I have balanced the oxidation half-equation.[1]
- ✓ ✗ I have balanced the reduction half-equation.[2]

b. i. Oxidation: $Ni(s)/Ni^{2+}(aq)$

ii. Reduction: $Ag^+(aq)/Ag(s)$

c. $Ni^{2+}(aq) + 2Ag(s) \rightarrow Ni(s) + 2Ag^+(aq)$

FROM LESSONS 3A & 3B

17. a. [No.[1]][This is a spontaneous redox reaction because a sufficient voltage from an external power source was not necessary for this reaction to occur.[2]]

- ✓ ✗ I have identified whether the reaction is electrolytic.[1]
- ✓ ✗ I have explained my answer.[2]

b. $Cu(s) + Pb^{2+}(aq) \rightarrow Cu^{2+}(aq) + Pb(s)$

FROM LESSONS 3B & 3C

6B Electrolytic cells

Progress questions

1. C. The anode is always the site of oxidation. In an electrolytic cell, this is the positive electrode.

2. B. The positive electrode in a galvanic cell is the anode, which is the site of oxidation. The strongest reducing agent (bottom right on the electrochemical series) will be oxidised (lose electrons). Therefore, the correct answer is the oxidation of Sn^{2+} ions.

3. C. In order of appearance in the electrochemical series, the possible half-reactions of species present are:

$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$ $\quad E^0 = +1.77\ V$

$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$ $\quad E^0 = +1.36\ V$

$O_2(g) + 4H^+(aq) + 4e^- \leftarrow 2H_2O(l)$ $\quad E^0 = +1.23\ V$

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ $\quad E^0 = +0.34\ V$

$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$ $\quad E^0 = -0.83\ V$

The strongest oxidising agent (top left: Cu^{2+}) is predicted to be reduced by the strongest reducing agent (bottom right: H_2O) according to the following equations.

Reduction: $Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$ $\quad E^0 = +0.34\ V$

Oxidation: $2H_2O(l) \rightleftharpoons O_2(g) + 4H^+(aq) + 4e^-$ $\quad E^0 = +1.23\ V$

$E_{required} > E^0_{most\ positive\ value\ (oxidation)} - E^0_{least\ positive\ value\ (reduction)}$

$E_{required} > +1.23\ V - (+0.34\ V)$

$E_{required} > +0.89\ V$

4. A. The product at the cathode is produced by the reduction of the strongest oxidising agent (top left).

Option A: oxidising agents present are $K^+(aq)$ and $H_2O(l)$. According to the electrochemical series, the stronger oxidising agent is $H_2O(l)$, which would be reduced according to:

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

Hydrogen gas would be produced.

Option B: oxidising agent present is $Na^+(l)$, which would be reduced to $Na(l)$.

Option C: oxidising agent present is $Pb^{2+}(l)$, which would be reduced to $Pb(s)$.

Option D: oxidising agents present are $Cu^{2+}(aq)$ and $H_2O(l)$. The stronger oxidising agent, $Cu^{2+}(aq)$, would be reduced to $Cu(s)$.

5. A. The half-reactions occurring in the electroplating cell are:

Anode (oxidation): $Ni(s) \rightarrow Ni^{2+}(aq) + 2e^-$

Cathode (reduction): $Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

Prior to the change, Ni^{2+} ions are produced at the anode and consumed at the cathode, so the amount of Ni^{2+} ions in the electrolyte remains constant.

If the amount of Ni electroplated decreases following the change to the cell, the change must cause either an alternative reduction half-reaction to be favoured, or a decrease in the amount of Ni^{2+} ions available to be reduced.

If the Ni electrode is replaced with a Cu electrode (option A), Ni^{2+} ions will not be produced at the anode, so as reduction occurs at the cathode (and $Ni^{2+}(aq)$ is converted to $Ni(s)$), the amount of Ni^{2+} ions in the electrolyte will decrease. Therefore, the amount of Ni that can be deposited will be reduced.

Options B, C, and D do not affect the half-reactions that occur in this cell.

Deconstructed

6. B **7.** A

8. [$Mn^{2+}(aq)$ is a weaker oxidising agent than water (strongest oxidising agent will be towards the top left of the electrochemical series), so it cannot be converted to Mn(s) to plate the boot, as the strongest oxidising agent present is always predicted to be reduced under SLC in electrolytic reactions.[1]][The reduction half-reaction involving water is favoured until the reaction occurs to completion.[2]][Therefore, the boot is not predicted to be plated with Mn.[3]]

- ✓ ✗ I have identified the strongest oxidising agent present.[1]
- ✓ ✗ I have stated that water will be reduced until the reaction occurs to completion.[2]
- ✓ ✗ I have linked my explanation to a prediction.[3]

Exam-style

9. C. Option A: the cathode is always the site of reduction.

Option B: only the products of electrolytic reactions must be separated.

Option C: electrolytic reactions are a type of redox reaction (transfer of electrons between species).

Option D: Electrolytic cells convert electrical energy into chemical energy.

10. C. Cryolite lowers the melting temperature of Al_2O_3, meaning that the electrolytic cell in which this reaction takes place does not require such extreme temperatures to operate. Therefore, the addition of cryolite means that it is less expensive for this cell to run.

11. C. Predictions based on the electrochemical series are most accurate at 25 °C and 100 kPa, using 1.0 M solutions, but the principle of 'strongest oxidising agent reacts with strongest reducing agent' may be utilised to determine the most likely electrode reactions for this molten mixture. Possible half-reactions are:

Anode (+) (oxidation): $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$
or $2F^-(l) \rightarrow F_2(g) + 2e^-$

Cathode (−) (reduction): $Na^+(l) + e^- \rightarrow Na(l)$
or $Al^{3+}(l) + 3e^- \rightarrow Al(s)$

Al^{3+} is a stronger oxidising agent than Na^+, so aluminium will be produced at the cathode.

Cl^- is a stronger reducing agent than F^-, so chlorine will be produced at the anode.

12. a. [The prediction stated implies that the student believed that water is the strongest oxidising or reducing agent, resulting in the production of hydrogen or oxygen gas respectively.[1]][However, according to the electrochemical series, the tin(II) (Sn^{2+}) ion is both the strongest oxidising agent and the strongest reducing agent, so it would be reduced to solid tin and oxidised to tin(IV) (Sn^{4+}) ions respectively.[2]][As a result, no bubbles would have been observed in the reaction.[3]]

- ✓ ✗ I have identified the reason for the student's prediction.[1]
- ✓ ✗ I have used the electrochemical series to account for the unexpected observation.[2]
- ✓ ✗ I have explained the observation.[3]

b. [Anode: $Sn^{2+}(aq) \rightarrow Sn^{4+}(aq) + 2e^-$[1]]
[Cathode: $Sn^{2+}(aq) + 2e^- \rightarrow Sn(s)$[2]]

- ✓ ✗ I have written the oxidation half-reaction at the anode.[1]
- ✓ ✗ I have written the reduction half-reaction at the cathode.[2]

c. The use of molten reactants would eliminate the presence of water, yet tin(II) ions would still be both the strongest oxidising and reducing agent present. Therefore, there would be no change in the overall reaction in the cell.

13. a. [For the desired reaction to occur, a molten electrolyte should be used.[1]][If an aqueous electrolyte were used, since water is a stronger oxidising agent than lithium ions, water would be reduced, and hence lithium metal would not be produced.[2]]

- ✓ ✗ I have used the electrochemical series to justify my answer.[1]
- ✓ ✗ I have identified whether a molten or an aqueous electrolyte is required.[2]

b. i. [With an iron anode, iron is the strongest reducing agent present,[1]][and so the reaction at the anode will be $Fe(s) \rightarrow Fe^{2+}(l) + 2e^-$.[2]][With an iron cathode, iron will not take part in the reaction as it is not able to be reduced and it is not available to react at the anode.[3]][Consequently, the reaction at the anode will be $2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$.[4]]

- ✓ ✗ I have predicted whether iron will be involved in a half-reaction as the anode.[1]
- ✓ ✗ I have correctly written the reaction occurring at the anode in cell 1.[2]
- ✓ ✗ I have predicted whether iron will be involved in a half-reaction as the cathode.[3]
- ✓ ✗ I have correctly written the reaction occurring at the anode in cell 2.[4]

ii. [The desired reaction is the conversion of lithium ions to solid lithium.[1]][The iron anode is a stronger reducing agent than $Cl^-(l)$ and could be oxidised in this reaction, meaning that it may crumble in cell 1.[2]][The carbon anode is inert and does not react, so does not affect the reaction.[3]][Therefore, the carbon anode in cell 2 would result in the desired reaction and the electrode not crumbling.[4]]

- ✓ ✗ I have identified the desired reaction.[1]
- ✓ ✗ I have identified the reaction predicted with an iron anode.[2]
- ✓ ✗ I have identified the reaction predicted with a carbon electrode.[3]
- ✓ ✗ I have identified the cell predicted to facilitate the desired reaction.[4]

c. [The voltage required for the reaction between Cl^- and Li^+ to occur is given by

$E_{required} > E^0_{most\ positive\ value\ (oxidation)} - E^0_{least\ positive\ value\ (reduction)}$ [1]]

[$E_{required} > +1.36\ V - (-3.04\ V) = +4.40\ V$[2]]

[As the supplied voltage, 1.05 V, is less than the required voltage, 4.40 V, it is expected that the reaction will not occur, and so solid lithium will not be produced.[3]]

- I have written the formula to calculate the voltage required for the cell to operate.[1]
- I have calculated the required voltage.[2]
- I have explained why the reaction is not predicted to occur by comparing the required voltage to the voltage supplied.[3]

Key science skills

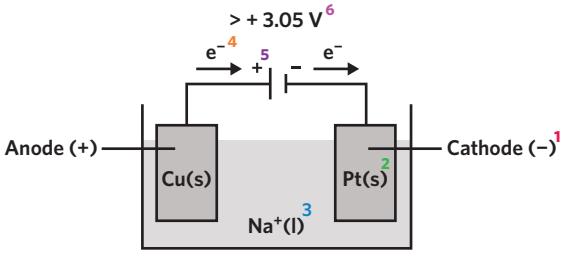
14. a. [The electrochemical series shows that water is a stronger oxidising agent (top left) than sodium ions, and so are predicted to be reduced in preference.[1]] [The presence of water in an aqueous electrolyte changes the reaction, meaning the desired product, sodium metal, is no longer produced. The use of a molten reactant would eliminate this issue.[2]] [However, using a molten electrolyte would add significant cost to the project, due to the high temperatures required.[3]] [Since a molten electrolyte must be used, a carbon (graphite) electrode may be used instead of a platinum electrode, as it is much cheaper.[4]]

- I have identified that water is a stronger oxidising agent than Na^+.[1]
- I have described the effect of the electrolyte on the product obtained.[2]
- I have described the effect of the electrolyte on the cost of the project.[3]
- I have identified a way to minimise operating costs.[4]

Alternative answer:

- An additive that reduces the melting point of the electrolyte may be added to reduce operating temperatures, which would reduce operating costs.

b.



- I have correctly labelled both electrodes and their polarity.[1]
- I have correctly labelled the material of each electrode.[2]
- I have correctly labelled the electrolyte including states.[3]
- I have correctly labelled the direction of flow of electrons.[4]
- I have correctly included the power supply.[5]
- I have correctly predicted the required voltage input.[6]

c. [The safety data sheet indicates that sodium may ignite when in contact with water.[1]] [As a result, the company should store the sodium samples in a dry, airtight container or under oil to minimise the chance of explosion.[2]]

- I have identified a relevant risk from the Safety Data Sheet.[1]
- I have stated an appropriate measure to reduce this risk.[2]

Alternative answers:

- Sodium may cause severe skin burns and eye damage. Protective gloves and glasses should be worn while handling samples.
- Sodium releases flammable gases when exposed to water. Sodium should be used in a well-ventilated area.

FROM LESSONS 12B & 12D

15. a. Red

b. [Anode: oxygen (O_2)[1]]
[Cathode: hydrogen (H_2)[2]]

- I have predicted the gas produced at the anode.[1]
- I have predicted the gas produced at the cathode.[2]

c. i. $2NaCl(l) \rightarrow 2Na(l) + Cl_2(g)$

Alternative answer:

- $2Na^+(l) + 2Cl^-(l) \rightarrow 2Na(l) + Cl_2(g)$

ii. [It would be difficult to maintain the required temperature at or above 801 °C.[1]] [There may be a lack of correct equipment to safely collect or remove toxic $Cl_2(g)$.[2]]

- I have suggested a reason.[1]
- I have suggested a different reason.[2]

Alternative answers:

- Danger keeping temperature at or above 801 °C
- Difficulty keeping produced Na away from air
- Difficulty keeping Na and Cl_2 from coming into contact (violent spontaneous reaction)
- Issues sourcing suitable electrodes
- Issues with maintaining the electric circuit at this high temperature

FROM LESSON 12B

Questions from multiple lessons

16. [Statement 1:[1]][Only electrolytic cells require a power supply to operate.[2]][Statement 3:[3]][The anode and cathode of primary galvanic cells (negative (−) anode, positive (+) cathode) have opposite polarities compared to the anode and cathode of electrolytic cells (positive (+) anode, negative (−) anode).[4]]

- ✓ ✗ I have stated that Statement 1 is incorrect.[1]
- ✓ ✗ I have given a correct statement by rewriting Statement 1.[2]
- ✓ ✗ I have stated that Statement 3 is incorrect.[3]
- ✓ ✗ I have given a correct statement by rewriting Statement 3.[4]

FROM LESSON 3C

17. a. [Reduction: $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$[1]]
[Oxidation: $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$[2]]

- ✓ ✗ I have written a reduction half-equation including state symbols.[1]
- ✓ ✗ I have written an oxidation half-equation including state symbols.[2]

b. [No.[1]][Unlike an electrolytic reaction, this reaction does not require a voltage from a power supply to be applied for it to occur.[2]]

- ✓ ✗ I have identified whether this is an electrolytic reaction.[1]
- ✓ ✗ I have explained my answer.[2]

c. Anode: Aluminium

Cathode: Metal in brackets of braces

d. [Yes.[1]][The electrolyte consists of dissolved ionic salts in saliva.[2]][These allow ions to flow between electrodes (forming the 'internal circuit').[3]]

- ✓ ✗ I have stated whether an electrolyte is present.[1]
- ✓ ✗ I have identified the electrolyte.[2]
- ✓ ✗ I have explained the role of the electrolyte.[3]

e. $E_{required} > E^0_{most\ positive\ value\ (oxidation)} - E^0_{least\ positive\ value\ (reduction)}$

$E_{mouth} = -0.83\ V - (-1.66\ V)$

$E_{mouth} = +0.83\ V$

f. There is no second electrode for current to flow to (through the 'external circuit'), so no reaction occurs.

FROM LESSONS 3B, 3C & 6A

6C Secondary cells

Progress questions

1. B. Primary galvanic cells are not reusable/are non-rechargeable. Secondary cells are rechargeable batteries; they can be connected to a power supply so that their contents undergo electrolysis, allowing the cell to be reused.

2. C. Option A: Only secondary cells (rechargeable batteries) can be recharged.

Option B: The cathode (site of reduction) is positive during discharge (primary galvanic cell reaction)

Option D: The anode (site of oxidation) is positive during recharge (electrolysis reaction)

3. D. During recharge, a voltage input from a power supply initiates a non-spontaneous redox (electrolytic) reaction, causing the battery to act as an electrolytic cell (conversion of electrical energy into chemical energy).

4. A. In a secondary cell (rechargeable battery), the discharge reaction (chemical energy → electrical energy) is the reverse reaction of the recharge reaction (electrical energy → chemical energy).

5. A. Oxidation (loss of electrons) always occurs at the anode, and the recharge reaction in a secondary cell is the reverse reaction of the discharge reaction. Options B and C both show reduction half-reactions, and option D shows the oxidation half-reaction that occurs during discharge (zinc is only present in the products during the recharge reaction).

6. B.

$E_{required} > E^0_{most\ positive\ value\ (oxidation)} - E^0_{least\ positive\ value\ (reduction)}$

$E_{required} > E^0(Cu^{2+}/Cu) - E^0(Zn^{2+}/Zn)$

$E_{required} > +0.34\ V - (-0.76\ V)$

$E_{required} > +1.10\ V$

7. A. Aqueous products of discharge reactions remain in contact with the electrode at which they react more easily than solid species. Therefore, it is ideal for secondary cells to contain predominantly aqueous species.

Deconstructed

8. D **9.** A

10. [The overall recharge reaction is $Na_2S_3(s) \rightarrow 2Na(l) + 3S(l)$.[1]]
[If the discharge product (solid Na_2S_3) is not in contact with the electrode battery, life/efficiency is reduced[2]][because this product of the discharge reaction would not be able to be electrolysed during the recharge reaction.[3]]

- ✓ ✗ I have provided a recharge overall equation or half-equation that contains Na_2S_3 as a reactant.[1]
- ✓ ✗ I have identified a factor that may decrease the cell's ability to be recharged.[2]
- ✓ ✗ I have explained this factor.[3]

Alternative answers:

- Side reactions reduce the efficiency of the cell by reducing the amount of useful product that can be recharged.
- High temperatures increase the possibility of side reactions.
- Low temperatures increase the possibility of crystallisation.

Exam-style

11. a. $E_{cell} = E^0(\text{most positive value}) - E^0(\text{least positive value})$

$E_{cell} = +0.60\text{ V} - (-0.82\text{ V})$

$E_{cell} = +1.42\text{ V}$

b. $E_{required} > E^0(\text{most positive value}) - E^0(\text{least positive value})$

$E_{required} > +0.60\text{ V} - (-0.82\text{ V})$

$E_{required} > +1.42\text{ V}$

c. The half-reaction with the highest standard electrode potential is predicted to be the reduction half-reaction, which occurs at the cathode (site of reduction).

$2NiO(OH)(s) + 2H_2O(l) + 2e^- \rightarrow 2Ni(OH)_2(s) + 2OH^-(aq)$

12. a. [$2PbSO_4(s) + 2H_2O(l)$[1]][$\rightarrow Pb(s) + PbO_2(s) + 2SO_4^{2-}(aq) + 4H^+(aq)$[2]]

✓ ✗ I have included the correct balanced reactants with states.[1]

✓ ✗ I have included the correct balanced products with states.[2]

b. The lead electrode. The recharge reaction is the reverse reaction of the discharge reaction. Reduction (gain of electrons) always occurs at the cathode. The reverse reaction of an oxidation half-reaction will be a reduction half-reaction.

c. Solid products must remain in contact with the electrodes at which they react in order to be electrolysed (and hence recharged).

13. a. A primary cell cannot be recharged, whereas a secondary cell can be recharged.

Alternative answer:

- In a primary cell, the products of discharge move away from the electrodes.

b. i. → (from left to right). As the discharge reaction is the reverse reaction of the recharge reaction, the anode (site of oxidation: loss of electrons) during recharge will be the cathode (site of reduction: gain of electrons) during discharge. Electrons always flow from the anode towards the cathode in electrochemical cells.

ii. → (from left to right). As the discharge reaction is the reverse reaction of the recharge reaction, the anode (site of oxidation: loss of electrons) during recharge will be the cathode (site of reduction: gain of electrons) during discharge. Cations always flow towards the cathode in electrochemical cells.

14. D. The recharge reaction is the reverse reaction of the discharge reaction and involves the conversion of electrical energy to chemical energy.

$2PbSO_4(s) + 2H_2O(l) \rightarrow Pb(s) + PbO_2(s) + 4H^+(aq) + 2SO_4^{2-}(aq)$

Since $[H^+]$ increases, the pH decreases.

15. A. Electrons always flow from the anode towards the cathode through the external circuit (wire). Cations flow towards the cathode through the internal circuit (electrolyte). This indicates that Cycle 1 has a positive cathode and negative anode. This is characteristic of a discharge reaction, during which energy is produced during a spontaneous reaction. Cycle 2 has a positive anode and a negative cathode. This is characteristic of a recharge reaction, which requires an energy input to initiate the reaction.

16. a. $Zn(s) + 2Ce(CH_3SO_3)_4(aq) \rightarrow 2Ce(CH_3SO_3)_3(aq) + Zn(CH_3SO_3)_2(aq)$

or $Zn(s) + 2Ce^{4+}(aq) \rightarrow Zn^{2+}(aq) + 2Ce^{3+}(aq)$

b. [The oxidising agent is $Ce(CH_3SO_3)_4$ or Ce^{4+},[1]][as the oxidation number of Ce decreases from +4 in $Ce(CH_3SO_3)_4$ to +3 in $Ce(CH_3SO_3)_3$.[2]]

✓ ✗ I have identified the correct oxidising agent.[1]

✓ ✗ I have justified my answer using oxidation states.[2]

c. $E_{cell} = E^0(\text{most positive}) - E^0(\text{least positive})$

$E_{cell} = +1.64\text{ V} - (-0.76\text{ V})$

$E_{cell} = +2.40\text{ V}$

d. The anode (site of oxidation: loss of electrons) is positive during recharge reactions. In electrolytic reactions, the oxidation half-reaction has the highest E^0 value. Therefore, the following half-reaction occurs.

$Ce(CH_3SO_3)_3(aq) + CH_3SO_3^-(aq) \rightarrow Ce(CH_3SO_3)_4(aq) + e^-$

or $Ce(CH_3SO_3)_3(aq) + CH_3SO_3H(aq) \rightarrow Ce(CH_3SO_3)_4(aq) + H^+(aq) + e^-$

or $Ce^{3+}(aq) \rightarrow Ce^{4+}(aq) + e^-$

e. To prevent the oxidising agent and reducing agent from coming into direct contact

Alternative answers:

- To separate the two half-cells
- To prevent the excessive release of thermal energy in the cell
- To prevent spontaneous redox reaction occurring when the reducing agent and oxidising agent come into contact with each other

f. Side reactions at the electrodes

Alternative answers:

- Loss/breakdown/oxidation/corrosion of the Zn electrode
- Electrolysis of water during recharging
- Significant temperature change
- Build-up of gases around electrode

g. [Fuel cell: supply of reactants ($Zn^{2+}/Ce^{4+}/Ce^{3+}$) from outside the cell.[1]][Secondary cell: rechargeable/discharge reaction can be reversed.[2]]

✓ ✗ I have identified a fuel cell property of this cell.[1]

✓ ✗ I have identified a secondary cell property of this cell.[2]

Key science skills

17. B. The answer in an addition/subtraction calculation is expressed to the least decimal places used in the calculation. The answer to this calculation is 0.65 V, and the lowest number of decimal places used in the calculation is 2, so this result does not need to be expressed to a different number of decimal places. An answer of 0.65 V has two significant figures (leading zeroes are not significant).

FROM LESSON 12E

18. a. $2Li_2CO_3 + C \rightarrow 4Li + 3CO_2$

b. [Battery life would be reduced.[1]][As lithium carbonate breaks away from the cathode, this reduces the amount of Li_2CO_3 available for recharging.[2]]

- I have described the effect on battery performance.[1]
- I have described how this affected the performance of the battery.[2]

Alternative answers:

Effect:

- Performance reduced
- Limits the extent of recharging/number of recharges
- Reduced ability to hold full charge

Description:

- Discharge products need to stay in contact with electrodes for effective recharge.

c. [Li(s) is a very strong reducing agent and will reduce water to produce $H_2(g)$.[1]][$2Li(s) + 2H_2O(l) \rightarrow H_2(g) + 2Li^+(aq) + 2OH^-(aq)$[2]][Hydrogen gas is highly explosive.[3]]

- I have identified the product(s) that cause(s) a potential safety concern.[1]
- I have provided either both half-equations or the overall equation for a relevant redox reaction.[2]
- I have explained why this chemical poses a safety risk.[3]

Alternative answers:

Product and risk:

- Build-up of H_2 leading to a potential explosion due to pressure or spontaneous combustion.

Equation:

- $Li(s) \rightarrow Li^+(aq) + e^-$ / $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

d. No. The $CO_2(g)$ absorbed during discharge will be released during recharge.

FROM LESSON 12B

19. a. [No, NaBr(s) is not suitable as an electrolyte.[1]][NaBr(s) is an ionic solid in which the ions are unable to move between electrodes.[2]][Electrolytes must allow for the free movement of charged particles (ions) between the electrodes.[3]]

- I have determined that NaBr(s) is not a suitable electrolyte.[1]
- I have explained why NaBr(s) is not a suitable electrolyte.[2]
- I have identified an essential requirement of an electrolyte.[3]

b. [Replace the Na in the electrode with another metal (Ca, K)[1]] [to give a higher electrode potential (V).[2]][The cell may be isolated to prevent reactions with oxygen and water.[3]]

- I have suggested an improvement.[1]
- I have justified my improvement.[2]
- I have suggested a safety consideration.[3]

Alternative answers:

Improvement:

- Replace the Na in the electrode with a less reactive metal (e.g. Fe) to improve safety.
- Replace Br in the complex electrode with Cl for a higher electrode potential.
- Replace NaBr with another molten electrolyte that allows transport of ions. (The replacement electrolyte must not react with Na in the electrodes so it cannot be aqueous.)

FROM LESSONS 12B & 12E

Questions from multiple lessons

20. [Sunlight increases the temperature of the battery in the phone, which would increase the rate of the redox reactions occurring in the battery,[1]][leading to the battery undergoing discharge more quickly. As a result, the battery would be drained a lot more quickly.[2]]

- I have identified the effect of a temperature increase on the rate of reaction.[1]
- I have described the effect of a temperature increase on battery function.[2]

FROM LESSON 4A

21. a. [$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$[1]] [$\Delta H = -2220$ kJ mol^{-1} [2]]

- I have correctly balanced the equation with correct states.[1]
- I have included the correct ΔH value including the sign.[2]

b. $m(C_3H_8) = d \times V$

$m(C_3H_8) = 0.510$ kg L$^{-1} \times 33.7$ L

$m(C_3H_8) = 17.187$ kg (1 MARK)

VCE Data Book: Heat of combustion for propane = 50.5 kJ g^{-1}

Energy released = 50.5 kJ g$^{-1} \times (17.187 \times 10^3$ g)

Energy released = 8.68×10^5 kJ (1 MARK)

c. i. Positive or (+)

ii. [$C_3H_8 + 6H_2O$[1]][$\rightarrow 3CO_2 + 20H^+ + 20e^-$[2]]

✓ ✗ I have included the correct balanced reactants.[1]

✓ ✗ I have included the correct balanced products.[2]

iii. Reactants are continuously supplied to the fuel cell, whereas there is a fixed quantity of reactants at the start of the secondary cell life and the amount decreases during discharge.

Alternative answers:

- Products move out of the fuel cell, whereas in a secondary cell the products can remain in contact with the electrodes.
- The fuel cell produces greenhouse gases, whereas the secondary cell does not.

FROM LESSONS 1D, 2A & 3E

6D Designing cells to produce green hydrogen

Progress questions

1. B. Green hydrogen must have no carbon emissions during its production.

2. D. The major limiting factor of large-scale green hydrogen production is the cost of the renewable energy sources required.

3. A. Given the cost involved in all the other options, adding a green fuel to a fossil fuel will help reduce carbon emissions and improve sustainability in the very near future.

4. A. Many ions that are stronger oxidising agents than water could be reduced, which would significantly affect the operation of the electrolyser.

5. B. In order for the electrolyser to function correctly, the water must be a liquid when electrolysis occurs.

6. D. Both processes involve redox reactions involving water, oxygen and carbon dioxide.

7. C. Artificial photosynthesis produces hydrogen as its main store of energy, unlike photosynthesis, which creates sugars.

8. B. Hydrogen gas initially has an oxidation state of zero, and when it reacts with either nitrogen or carbon dioxide, it gives away an electron to gain an oxidation state of +1 and is therefore oxidised. Given reducing agents are oxidised in redox reactions, hydrogen acts as a reducing agent. Note that reduction can also be defined as a loss of oxygen or a gain in hydrogen.

Deconstructed

9. B **10.** A **11.** B

12. $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ or $H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)$

Exam-style

13. [Cost of materials[1]][and scaling up the technology to be used on a larger scale that is capable of supplying enough energy to keep up with demand.[2]]

✓ ✗ I have identified one challenge preventing the mainstream use of artificial photosynthesis.[1]

✓ ✗ I have identified a second challenge preventing the mainstream use of artificial photosynthesis.[2]

14. [Similarities: Both half-cells use a proton conducting membrane.[1]] [Both half-cells are separated by the membrane, which does not allow electrons to conduct across it.[2]][Differences: The PEM electrolyser is designed to receive electrical energy from different sources (wind, biomass, and solar), whereas artificial photosynthesis requires solar energy from the sun in the form of visible light.[3]][Artificial photosynthesis uses wires (nano-sized) to absorb visible light, whereas the PEM electrolyser does not use any rods in its design.[4]]

✓ ✗ I have explained a similarity in the design of both cells.[1]

✓ ✗ I have explained a second similarity in the design of both cells.[2]

✓ ✗ I have explained a difference in the design of both cells.[3]

✓ ✗ I have explained a second difference in the design of both cells.[4]

Alternative answer:

Similarity:

- Both processes have electrodes that are covered in specific catalysts.

Key science skills

15. a. [The actual processes involved in the creation of green hydrogen using a PEM electrolyser do not create any net carbon emissions as they are created using only renewable resources.[1]][The production, transport and maintenance of all of the equipment will not be carbon neutral as many of these processes will still use fossil fuels as an energy source.[2]]

✓ ✗ I have discussed one valid point regarding the carbon neutrality of green hydrogen.[1]

✓ ✗ I have discussed another valid point regarding the carbon neutrality of green hydrogen.[2]

b. [Energy Efficiency: The process of producing green hydrogen can be energy-intensive, especially when using renewable energy sources that are costly to implement. This can reduce the overall efficiency of the process and increase costs.[1]] [Cost: Currently, the cost of green hydrogen production is higher than that of other conventional fuels. This can limit its use, especially in developing countries.[2]]

✓ ✗ I have discussed one valid point about the sustainability of green hydrogen.[1]

✓ ✗ I have discussed a second valid point about the sustainability of green hydrogen.[2]

c. [Zero carbon emissions: When green hydrogen is used as a fuel in transportation, it produces no harmful carbon emissions, but does emit the more harmful greenhouse gas, water vapour.[1]] [Infrastructure: There is currently limited infrastructure for

producing, storing, and transporting hydrogen. This can make it challenging to scale up the use of hydrogen as a fuel source.[2]]

✓ ✗ I have discussed one valid point about the use of green hydrogen as a fuel for transport.[1]

✓ ✗ I have discussed a second valid point about the use of green hydrogen as a fuel for transport.[2]

Alternative answer:

- Water Resources: Hydrogen production requires significant amounts of water, which can be a challenge in areas facing water scarcity or drought.

FROM LESSON 12E

Questions from multiple lessons

16. a. [Catalysts play a crucial role in artificial photosynthesis by lowering the activation energy required for specific reactions to occur. This reduction in activation energy allows the reactions to proceed more quickly and with less energy input.[1]][In the water oxidation process, a catalyst helps break down water molecules into oxygen and protons according to the following equation: $2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^-$.[2]][Similarly, in the proton reduction process, a catalyst assists in converting protons and electrons into molecular hydrogen according to the following equation: $4H^+(aq) + 4e^- \rightarrow 2H_2(g)$.[3]]

✓ ✗ I have explained that catalysts allow reactions to proceed more quickly and with less energy input.[1]

✓ ✗ I have described the action of a catalyst in the water oxidation process.[2]

✓ ✗ I have described the action of a catalyst in the proton reduction process.[3]

b. [X: Hydrogen ions, $H^+(aq)$.[1]][Y: Electrons, e^-.[2]]
[Z: Hydrogen gas, $H_2(g)$.[3]]

✓ ✗ I have identified the chemical species represented by X.[1]

✓ ✗ I have identified the chemical species represented by Y.[2]

✓ ✗ I have identified the chemical species represented by Z.[3]

Alternative answers:

- Y: Hydrogen ions, $H^+(aq)$, X: Electrons, e^-, Z: Hydrogen gas, $H_2(g)$.

FROM LESSON 4B

17. a. From the VCE Data Book:

$E^0(\text{oxidation reaction}) = +1.23\text{ V}$

$E^0(\text{reduction reaction}) = 0.00\text{ V}$

$E_{\text{required}} > E^0(\text{most positive value: oxidation}) - E^0(\text{least positive value: reduction})$

$E_{\text{required}} > +1.23\text{ V} - 0.00\text{ V}$

$E_{\text{required}} > +1.23\text{ V}$

b. $q = VIt$

$q = 1.23\text{ V} \times 2.00\text{ A} \times (2 \times 60 \times 60)\text{ s}$

$q = 1.77 \times 10^4\text{ J}$

$q = 17.7\text{ kJ}$

Hence, at least 17.7 kJ is required.

c. $Q = It$

$Q = 2.00\text{ A} \times (2 \times 60 \times 60)\text{ s}$

$Q = 1.44 \times 10^4\text{ C}$ (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{1.44 \times 10^4\text{ C}}{96\,500\text{ C mol}^{-1}}$

$n(e^-) = 0.1492\text{ mol}$ (1 MARK)

From the half-equation $2H^+(aq) + 2e^- \rightarrow H_2(g)$:

$n(H_2) = \frac{n(e^-)}{2}$

$n(H_2) = \frac{0.1492\text{ mol}}{2}$

$n(H_2) = 0.0746\text{ mol}$ (1 MARK)

d. The sun

e. From VCE Data Book, $\Delta H(\text{octane}) = 47.9\text{ kJ g}^{-1}$ (1 MARK)

At 100% efficiency:

$m(\text{octane}) = \frac{q}{\Delta H}$

$m(\text{octane}) = \frac{17.7\text{ kJ}}{47.9\text{ kJ g}^{-1}}$

$m(\text{octane}) = 0.3695\text{ g}$ (1 MARK)

At 60% efficiency:

$m(\text{octane}) = m(\text{octane: 100\% efficiency}) \times \frac{100}{100 - 40}$

$m(\text{octane}) = 0.3695\text{ g} \times \frac{100}{60}$

$m(\text{octane}) = 0.616\text{ g}$ (1 MARK)

FROM LESSONS 1C, 1D, 2A, 2B, 3F & 6B

6E Faraday's Laws in electrolytic cells

Progress questions

1. A. $n(Cr) = \frac{1}{3} \times n(e^-)$

$n(Cr) = \frac{1}{3} \times 1.0\text{ mol}$

$n(Cr) = 0.33\text{ mol}$

2. B. $Q = It$

$t = \frac{Q}{I}$

$t = \frac{1554\text{ C}}{2.00\text{ A}}$

$t = 777\text{ s}$

3. A. $n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{1554\ C}{96\ 500\ C\ mol^{-1}}$

$n(e^-) = 0.01610\ mol$

$n(Cu) = \frac{1}{2} \times n(e^-)$

$n(Cu) = \frac{1}{2} \times 0.01610\ mol$

$n(Cu) = 0.008052\ mol$

$m(Cu) = n(Cu) \times M(Cu)$

$m(Cu) = 0.008052\ mol \times 63.5\ g\ mol^{-1}$

$m(Cu) = 0.511\ g$

4. A. $n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{4.00\ C}{96\ 500\ C}$

$n(e^-) = 4.15 \times 10^{-5}\ mol$

Deconstructed

5. D **6.** B **7.** C

8. D. $Q = It$

$Q = 5.0\ A \times 600\ s$

$Q = 3000\ C$

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{3000\ C}{96\ 500\ C\ mol^{-1}}$

$n(e^-) = 0.031088\ mol$

$m(metal) = \frac{n(e^-)}{x} \times M(metal)$

$m(metal) = \frac{0.031088\ mol}{x} \times M(metal)$

Option A: If metal cation is Ag^+, $x = 1$

$m(Ag\ deposited) = \frac{0.031088\ mol}{1} \times 107.9\ g\ mol^{-1}$

$m(Ag\ deposited) = 3.35\ g$

Option B: If metal cation is Ni^{2+}, $x = 2$

$m(Ni\ deposited) = \frac{0.031088\ mol}{2} \times 58.7\ g\ mol^{-1}$

$m(Ni\ deposited) = 0.91\ g$

Option C: If metal cation is Pb^{2+}, $x = 2$

$m(Pb\ deposited) = \frac{0.031088\ mol}{2} \times 207.2\ g\ mol^{-1}$

$m(Pb\ deposited) = 3.22\ g$

Option D: If metal cation is Cr^{3+}, $x = 3$

$m(Cr\ deposited) = \frac{0.031088\ mol}{3} \times 52.0\ g\ mol^{-1}$

$m(Cr\ deposited) = 0.54\ g$

Exam-style

9. B. $n(Au) = \frac{m}{M}$

$n(Au) = \frac{0.300\ g}{197.0\ g\ mol^{-1}}$

$n(Au) = 0.001523\ mol$

Gold is deposited at the cathode according to the balanced half-equation $Au^+(aq) + e^- \rightarrow Au(s)$.

$n(e^-) : n(Au)$

$1 : 1$

$n(e^-) = n(Au)$

$n(e^-) = 0.001523\ mol$

$Q = n(e^-) \times F$

$Q = 0.001523\ mol \times 96\ 500\ C\ mol^{-1}$

$Q = 146.954\ C$

$t = \frac{Q}{I}$

$t = \frac{146.954\ C}{2.00\ A}$

$t = 73\ s$

10. a. Chromium is deposited at the cathode according to the balanced half-equation $Cr^{3+}(aq) + 3e^- \rightarrow Cr(s)$. (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{4342.5\ C}{96\ 500\ C\ mol^{-1}}$

$n(e^-) = 0.045\ mol$

$n(Cr) : n(e^-)$

$1 : 3$

$n(Cr) = \frac{1}{3} \times 0.045\ mol$

$n(Cr) = 0.015\ mol$ (1 MARK)

b. [Chromium(III) ions have a charge of +3, whereas copper(II) ions have a charge of +2, so according to Faraday's second law, the amount of chromium deposited will be $\frac{2}{3}$ the amount of copper deposited.[1]][Na^+ is a weaker oxidising agent than water, so when an aqueous solution of $NaNO_3$ is electrolysed, no sodium will be deposited.[2]][As a result, the correct order of metals (from most to least number of moles deposited) is: copper, chromium, sodium.[3]]

✓ ✗ I have compared the amounts of copper and chromium deposited.[1]

✓ ✗ I have explained that no sodium will be deposited.[2]

✓ ✗ I have given the correct order of metals.[3]

11. a. $2H^+(aq) + 2e^- \rightarrow H_2(g)$

b. $t = (2.25 \times 60 \times 60)\ s$

$t = 8100\ s$

$Q = It$

$Q = 1.60\ A \times 8100\ s$

$Q = 12\ 960\ C$ (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{12\ 960\ C}{96\ 500\ C\ mol^{-1}}$

$n(e^-) = 0.1343\ mol$

$n(H_2) : n(e^-)$

1 : 2

$n(H_2) = \frac{1}{2} \times n(e^-)$

$n(H_2) = \frac{1}{2} \times 0.1343 \text{ mol}$

$n(H_2) = 0.06715 \text{ mol}$ (1 MARK)

$V(H_2) = n(H_2) \times V_m$

$V(H_2) = 0.06715 \text{ mol} \times 24.8 \text{ L mol}^{-1}$

$V(H_2) = 1.67 \text{ L}$ (1 MARK)

12. a. $Fe(s) \rightarrow Fe^{3+}(aq) + 3e^-$

b. $n(\text{Fe lost}) = \frac{m(\text{Fe lost})}{M(\text{Fe})}$

$n(\text{Fe lost}) = \frac{5.26 \text{ g}}{55.8 \text{ g mol}^{-1}}$

$n(\text{Fe lost}) = 0.094265 \text{ mol}$ (1 MARK)

$n(e^-) : n(\text{Fe})$

3 : 1

$n(e^- \text{ required}) = \frac{3}{1} \times n(\text{Fe lost})$

$n(e^- \text{ required}) = \frac{3}{1} \times 0.094265 \text{ mol}$

$n(e^- \text{ required}) = 0.2828 \text{ mol}$

$Q(\text{required}) = n(e^- \text{ required}) \times F$

$Q(\text{required}) = 0.2828 \text{ mol} \times 96\,500 \text{ C mol}^{-1}$

$Q(\text{required}) = 27\,290 \text{ C}$ (1 MARK)

$Q(\text{per tram}) = I(\text{per tram}) \times t(\text{per tram})$

$Q(\text{per tram}) = 3.6 \text{ A} \times 3.0 \text{ s}$

$Q(\text{per tram}) = 10.8 \text{ C}$ (1 MARK)

$\text{trams required} = \frac{Q(\text{required})}{Q(\text{per tram})}$

$\text{trams required} = \frac{27\,290 \text{ C}}{10.8 \text{ C}}$

trams required = 2526.83

minimum number of trams required to pass Phelin's house ≈ 2527 (1 MARK)

Key science skills

13. a. Volume of gas collected

Alternative answer:

- Current efficiency

b. The results are precise, since they are all within ± 0.3 mL of the mean values.

c. A small quantity of acid is added so that the water conducts electricity, making electrolysis possible.

d. $2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

Alternative answer:

- $2H^+(aq) + 2e^- \rightarrow H_2(g)$

e. i. $t = (5.00 \times 60) \text{ s}$

$t = 300 \text{ s}$

$Q = It$

$Q = 2.0 \text{ A} \times 300 \text{ s}$

$Q = 600 \text{ C}$

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{600 \text{ C}}{96\,500 \text{ C mol}^{-1}}$

$n(e^-) = 0.0062176 \text{ mol}$ (1 MARK)

From the reduction half-equation:

$n(H_2) : n(e^-)$

1 : 2

$n(H_2) = \frac{1}{2} \times 0.0062176 \text{ mol}$

$n(H_2) = 0.0031088 \text{ mol}$ (1 MARK)

$V(H_2 \text{ expected}) = n(H_2) \times V_m$

$V(H_2 \text{ expected}) = 0.0031088 \text{ mol} \times 24.8 \text{ L mol}^{-1}$

$V(H_2 \text{ expected}) = 0.0771 \text{ L}$

$V(H_2 \text{ expected}) = 77 \text{ mL (2 sig. figs)}$ (1 MARK)

ii. $V(H_2 \text{ produced}) = 170.0 \text{ mL} - 100.1 \text{ mL}$

$V(H_2 \text{ produced}) = 69.9 \text{ mL}$ (1 MARK)

$\text{current efficiency} = \frac{V(H_2 \text{ produced})}{V(H_2 \text{ expected})} \times 100\%$

$\text{current efficiency} = \frac{69.9 \text{ mL}}{77 \text{ mL}} \times 100\%$

current efficiency = 91% (1 MARK)

f. Current efficiency increases with concentration.

Alternative answer:

- The average volume of gas produced (H_2) at the negative electrode increases as the concentration of NaCl increases.

g. [The student should use higher concentrations of $Cl^-(aq)$[1]] [to ensure that only one oxidation reaction is occurring at the anode (rather than two, as it stands) and to hence more clearly see the effect on current efficiency.[2]]

✓ ✗ I have stated that the student should increase chloride concentration.[1]

✓ ✗ I have explained why this change helps the student achieve their aim.[2]

h. [The student should discuss whether the data supports or refutes their hypothesis.[1]] [The student should compare expected results to actual results.[2]]

✓ ✗ I have given a first aspect the student should include.[1]

✓ ✗ I have given a second aspect the student should include.[2]

Alternative answers:

- The student should analyse experimental design and errors.
- The student should relate the results to earlier work/theory (for example, the limitations of the electrochemical series).

FROM LESSONS 12A, 12B, 12C, 12D & 12E

Questions from multiple lessons

14. a. i. $2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

ii. $Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$

b. $t = (10.0 \times 60)$ s

$t = 600$ s

$Q = It$

$Q = 0.351 \text{ A} \times 600 \text{ s}$

$Q = 210.6 \text{ C}$ (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{210.6 \text{ C}}{96\,500 \text{ C mol}^{-1}}$

$n(e^-) = 0.0021824 \text{ mol}$ (1 MARK)

$n(Ni) : n(e^-)$

$1 \quad : \quad 2$

$n(Ni) = \frac{1}{2} \times n(e^-)$

$n(Ni) = \frac{1}{2} \times 0.0021824 \text{ mol}$

$n(Ni) = 0.0010912 \text{ mol}$

$m(Ni) = n(Ni) \times M(Ni)$

$m(Ni) = 0.0010912 \text{ mol} \times 58.7 \text{ g mol}^{-1}$

$m(Ni) = 0.064 \text{ g (2 sig. figs)}$ (1 MARK)

c. [If a lead cathode were used instead of a platinum cathode, there would be no change to the cell's function[1]][because reduction occurs at the cathode, and solid metals cannot be reduced. Therefore, lead (like platinum) would not react.[2]]

✓ ✗ I have identified that no change would occur.[1]

✓ ✗ I have explained why no change would occur.[2]

FROM LESSON 6B

15. a. $t = (2.0 \times 60)$ s

$t = 120$ s

$Q = It$

$Q = 1.20 \text{ A} \times 120 \text{ s}$

$Q = 144 \text{ C}$ (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{144 \text{ C}}{96\,500 \text{ C}}$

$n(e^-) = 1.492 \times 10^{-3} \text{ mol}$ (1 MARK)

$A^{x+} + xe^- \rightarrow A$

$n(e^-) = x \times n(\text{unknown metal})$

$x = \frac{n(e^-)}{n(\text{unknown metal})}$

$x = \frac{1.492 \times 10^{-3} \text{ mol}}{7.46 \times 10^{-4} \text{ mol}}$

$x \approx 2$ (1 MARK)

b. Water was the strongest reducing agent present, so it was oxidised according to the half-equation

$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \quad E^0 = +1.23 \text{ V}$ (1 MARK)

$E_{required} > E^0_{oxidation} - E^0_{reduction}$

$\text{min. } E_{required} = E^0_{oxidation} - E^0_{reduction}$

$E^0_{reduction} = E^0_{oxidation} - \text{min. } E_{required}$

$E^0_{reduction} = +1.23 \text{ V} - (+1.67 \text{ V})$

$E^0_{reduction} = -0.44 \text{ V}$

According to the electrochemical series, this corresponds with the reduction half-equation $Fe^{2+}(aq) + 2e^- \rightarrow Fe(s)$. (1 MARK)

FROM LESSON 6B

Chapter 6 review

Multiple choice

1. D. During the recharge cycle, electrical energy from the power supply is converted into chemical energy.

Option A: Undesirable side reactions may occur in secondary cells, potentially reducing cell rechargeability and longevity.

Option B: Fuel cells are not rechargeable.

Option C: In secondary cells, the cathode is positively charged during the discharge cycle and negatively charged during the recharge cycle.

2. B. Water is a reactant in the production of green hydrogen.

3. A. $Al^{3+}(l)$ is the strongest oxidising agent present, so it will be reduced at the cathode to form Al(l) according to $Al^{3+}(l) + 3e^- \rightarrow Al(l)$.

4. A. $n(Ag) = \frac{m}{M}$

$n(Ag) = \frac{0.150 \text{ g}}{107.9 \text{ g mol}^{-1}}$

$n(Ag) = 0.001390 \text{ mol}$

Since 1 mol of electrons is required per mol of Ag deposited,

$n(e^-) = n(Ag)$

$n(e^-) = 0.001390 \text{ mol}$

$Q = n(e^-) \times F$

$Q = 0.001390 \text{ mol} \times 96\,500 \text{ C mol}^{-1}$

$Q = 134.15 \text{ C}$

$t = \frac{Q}{I}$

$t = \frac{134.15 \text{ C}}{1.50 \text{ A}}$

$t = 89.4 \text{ s}$

5. C. $n(Au) = \frac{m}{M}$

$n(Au) = \frac{0.150 \text{ g}}{197.0 \text{ g mol}^{-1}}$

$n(Au) = 0.0007614 \text{ mol}$

Since 3 mol of electrons is required per mol of Au deposited,

$n(e^-) = 3 \times n(Au)$

$n(e^-) = 3 \times 0.0007614 \text{ mol}$

$n(e^-) = 0.002284$ mol

Since the current is the same for both scenarios, the ratio of $n(e^-)$ required will give the ratio of time required to plate the respective discs.

$n(e^-)_{\text{gold-plated}} : n(e^-)_{\text{silver-plated}}$

0.002284 mol : 0.0013902 mol

1.6 : 1

6. C. In electrochemical cells, electrons flow away from the anode (site of oxidation) and towards the cathode (site of reduction) in the external circuit.

In Cell 1: Electrons flow away from the zinc electrode, meaning Zn is oxidised at the anode. This means that in the other half-cell, Cu^{2+} is reduced at the cathode. Cu^{2+} (oxidising agent) appears above Zn (reducing agent) in the electrochemical series (Cu^{2+} is a stronger reducing agent than Zn^{2+}), so this redox reaction is spontaneous and Cell 1 behaves as a primary galvanic cell. Therefore, chemical energy is converted into electrical energy in Cell 1.

In Cell 2: Electrons flow towards the nickel electrode, meaning Ni^{2+} ions are reduced at the cathode. This means that in the other half-cell, Cu is oxidised at the anode. Ni^{2+} (oxidising agent) appears below Cu in the electrochemical series (Ni^{2+} is a weaker reducing agent than Cu^{2+}), so this redox reaction is non-spontaneous and Cell 2 behaves as an electrolytic cell. Therefore, electrical energy is converted into chemical energy in Cell 2.

7. A. HF is a molecule and does not produce ions when heated. HF dissociates in water, so aqueous HF contains water, H^+, and F^-. According to the electrochemical series, water is oxidised to form $O_2(g)$.

8. D. The relative positions of these metals in the electrochemical series are:

$Au^+(aq) + e^- \rightarrow Au(s)$ $\quad E^0 = +1.68$ V

$Ag^+(aq) + e^- \rightarrow Ag(s)$ $\quad E^0 = +0.80$ V

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ $\quad E^0 = +0.34$ V

$Ni^{2+}(aq) + 2e^- \rightarrow Ni(s)$ $\quad E^0 = -0.23$ V

$Co^{2+}(aq) + 2e^- \rightarrow Co(s)$ $\quad E^0 = -0.28$ V

$Fe^{2+}(aq) + 2e^- \rightarrow Fe(s)$ $\quad E^0 = -0.44$ V

$Zn^{2+}(aq) + 2e^- \rightarrow Zn(s)$ $\quad E^0 = -0.76$ V

Since pure copper is deposited at Electrode II, it must be the site of reduction (cathode).

At Electrode I, Cu and any metals that are stronger reducing agents (lower right of electrochemical series) than Cu (Zn, Co, Ni, Fe) will be oxidised to form aqueous ions.

Metals that are weaker reducing agents than water (Ag, Au) will not be oxidised and will collect under Electrode I as sludge. It is essential that Ag and Au are not oxidised at Electrode I, because their ions would be reduced in preference to $Cu^{2+}(aq)$ and would impact the purity of the Cu collected at Electrode II.

9. A. Since solid copper is deposited on Electrode II in this electrolytic cell, it can be deduced that $Cu^{2+}(aq)$ in the solution is reduced to Cu(s) at the cathode (site of reduction) according to the half-reaction $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$. As Electrode II is the cathode (site of reduction), Electrode I must be the anode (site of oxidation). In an electrolytic cell, the anode is positively (+) charged.

10. B. Since the metals in the electrode are oxidised, its mass must decrease with time.

Short answer

11. a. i. $Mg^{2+}(l) + 2e^- \rightarrow Mg(l)$

ii. $2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$

b. To prevent molten magnesium reacting with oxygen in the air

c. [According to the electrochemical series, both Na^+ and Ca^{2+} are weaker oxidising agents than Mg^{2+}, so are unlikely to interfere with the production of Mg at the cathode.[1]][However, Zn^{2+} is a stronger oxidising agent than Mg^{2+} and could be reduced to Zn, either preventing the production of Mg or contaminating the Mg produced.[2]]

✓ ✗ I have identified that Na^+ and Ca^{2+} are weaker oxidising agents than Mg^{2+}.[1]

✓ ✗ I have identified that Zn^{2+} is a stronger oxidising agent that Mg^{2+} and stated the implication of this for the production of Mg.[2]

d. [According to the electrochemical series, Fe is a stronger reducing agent than Cl^-. At the anode, Fe would be oxidised instead of Cl^-.[1]][Half-equation at anode: $Fe(s) \rightarrow Fe^{2+}(l) + 2e^-$ [2]] [Fe^{2+} is a stronger oxidising agent than Mg^{2+}, hence Fe could be produced, and the cathode half-reaction would be $Fe^{2+}(l) + 2e^- \rightarrow Fe(s)$.[3]]

✓ ✗ I have explained why Fe^{2+} is produced at the anode.[1]

✓ ✗ I have given the correct anode half-equation.[2]

✓ ✗ I have explained or given the half-equation for the production of Fe at the cathode.[3]

12. a. ↓ (down)

b. [The membrane allows H^+ ions/protons to pass through, completing the internal circuit.[1]][It also keeps H_2 and O_2 separate.[2]]

✓ ✗ I have stated a function of the membrane.[1]

✓ ✗ I have stated another function of the membrane.[2]

c. $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

d. i. $Q = It$

$Q = 1625.0 \text{ A} \times (1.25 \times 60 \times 60) \text{ s}$

$Q = 7.3125 \times 10^6 \text{ C}$ (1 MARK)

$n(e^-) = \frac{Q}{F}$

$n(e^-) = \frac{7.3125 \times 10^6 \text{ C}}{96\,500 \text{ C mol}^{-1}}$

$n(e^-) = 75.777 \text{ mol}$ (1 MARK)

$2H^+(aq) + 2e^- \rightarrow H_2(g)$

$n(H_2) = \frac{1}{2} \times n(e^-)$

$n(H_2) = \frac{1}{2} \times 75.777 \text{ mol}$

$n(H_2) = 37.9 \text{ mol}$ (1 MARK)

ii. $V(H_2) = n(H_2) \times V_m$

$V(H_2) = 37.9 \text{ mol} \times 24.8 \text{ L mol}^{-1}$

$V(H_2) = 940 \text{ L}$ (1 MARK)

e. [No.[1]][Carbon emissions may be involved in the manufacture, transport, and maintenance of the artificial photosynthesis cell, as many of these processes will still use fossil fuels as an energy source.[2]]

✓ ✗ I have stated whether artificial photosynthesis is carbon neutral.[1]

✓ ✗ I have explained my answer.[2]

13. [Place $MgCl_2$ in a crucible and heat until molten.[1]][Apply a voltage (greater than 3.73 V) using inert electrodes.[2]][Keep the Mg metal and chlorine gas (products) separated.[3]]

✓ ✗ I have identified that $MgCl_2$ must be molten.[1]

✓ ✗ I have stated that electrical energy must be supplied.[2]

✓ ✗ I have stated that products must be separated.[3]

14. a. i. $Br_2(aq) + 2H^+(aq) + 2e^- \rightarrow 2HBr(aq)$
or $Br_2(aq) + 2e^- \rightarrow 2Br^-(aq)$

ii. $QH_2(aq) \rightarrow Q(aq) + 2H^+(aq) + 2e^-$

b. $2HBr(aq) + Q(aq) \rightarrow Br_2(aq) + QH_2(aq)$
or $2Br^-(aq) + 2H^+(aq) + Q(aq) \rightarrow Br_2(aq) + QH_2(aq)$

c. i. ← (to the left)

ii. To prevent the oxidising agent and the reducing agent from coming into contact with each other

Alternative answers:

- To prevent a spontaneous direct reaction between the oxidising agent and the reducing agent
- To ensure that the cell can be recharged
- If the oxidising and reducing agents are allowed to come into contact, they can react together in the solution rather than individually at the electrodes.
- Chemical energy would be converted to thermal energy rather than electrical energy.

d. $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$

e. Rhubarb (the raw material for the quinones) can be readily replenished. Rhubarb is a plant-based source of quinones and can be easily produced as quickly as it is needed.

f. [All reactants and products in this cell are aqueous.[1]][This means that all species can easily remain in contact with the electrodes they react at, allowing the cell to be successfully recharged.[2]]

✓ ✗ I have identified a feature of this cell that affects its rechargeability.[1]

✓ ✗ I have explained how this feature affects the rechargeability of the cell.[2]

Key science skills

15. a. i. Complete the drying process with propanone in a fume hood.

Alternative answer:

- Do not use propanone near an open flame.

ii. Use a designated organic liquids disposal bottle.

b. i. Current

ii. [Time,[1]][to ensure that the charge (from $Q = It$) variation between trials is determined by the current only.[2]]

✓ ✗ I have identified a variable that should be controlled.[1]

✓ ✗ I have explained why this variable should be controlled.[2]

Alternative answers:

- Supplied voltage, to ensure voltage impact is the same in each trial and only current changes.
- Electrode location, to ensure the same amount of the electrolyte remains in contact with the electrodes between trials.
- Temperature, to ensure that the rate of reaction does not change between trials.

iii. [To find the effect of varying the current[1]][on the mass of the copper deposited during electrolysis.[2]]

✓ ✗ I have identified the independent variable and its role in the experiment.[1]

✓ ✗ I have identified the dependent variable and its role in the experiment.[2]

c. i. A graph (of mass of Cu plated against current)

Alternative answer:

- Only showing current and mass plated in the table

ii. [The class data could be collated and an average mass of Cu for each current could be calculated.[1]][If the collated data is consistent and shows that the mass of copper plated increased with increasing current, it would suggest the experiment is repeatable.[2]]

✓ ✗ I have suggested the average of the class data should be taken.[1]

✓ ✗ I have explained how this can be compared to the student's data.[2]

iii. [In this experiment, the mass of copper during electrolysis increased as the current increased.[1]][This was a linear relationship, and hence the mass of copper plated in a given time is directly proportional to the current.[2]]

✓ ✗ I have stated the trend in the data.[1]

✓ ✗ I have explained the relationship found between the independent and dependent variables.[2]

d. [Validity is increased by measuring the mass of both electrodes.[1]][If the increase in the mass in one electrode is not equal to the decrease in mass in the other electrode (within the uncertainty of the balance), then a random error is likely.[2]] [Since the mass of the plated copper is the difference between measured masses, systematic error should be minimised unless some copper produced does not adhere to the cathode or some copper falls off the anode without being oxidised.[3]]

- ✓ ✗ I have stated the effect on the validity of the method.[1]
- ✓ ✗ I have explained the effect on random error.[2]
- ✓ ✗ I have explained the effect on systematic error.[3]

FROM LESSONS 12A, 12B, 12C, 12D & 12E

7A Structures of organic compounds

Progress questions

1. D. Bond length, electronegativity differences, and the size of atoms affect bond strength. Note that the size of atoms does not always increase as atomic number increases.

2. B. Carbon bonds are generally relatively strong.

3. C. The structural formula shows all atoms and bonds in a molecule.

4. C. Alkenes follow the general formula C_nH_{2n}.

5. D. Each carbon atom can be involved in four bonds. Bonds between carbon atoms and hydrogen atoms are not shown in skeletal formulas.

6. C. Halogens may appear in any position in the carbon chain, depending on the molecule.

7. A. In primary amides, the oxygen and nitrogen atoms are both bonded directly to a carbon atom, and this functional group is only linked to a single alkyl group.

8. D. The molecular formula does not give any information about the position of each atom in the compound.

9. C. A primary alcohol involves an (−OH) functional group that is connected to a terminal carbon atom.

10. C. Ketones involve a carbon-oxygen double bond within the carbon chain. In aldehydes, oxygen shares a double bond with a terminal carbon.

11. A. Carboxylic acids contain a (−COOH) functional group.

12. C. Esters contain a (−COOC−) functional group.

Deconstructed

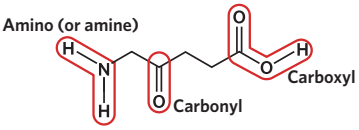
13. B

14. A

15. A. This compound does not contain nitrogen, so cannot be an amide. If it is an alcohol, a carbon-carbon double bond must be present to give the formula $C_6H_{12}O_2$. An aldehyde would require two aldehyde groups for the compound to contain 2 oxygen atoms; however, only ten hydrogen atoms would be present. An ester with the described features can be constructed.

Exam-style

16. B.

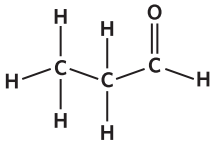


17. **a.** Amide group

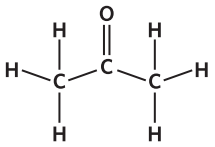
b. Amino or amine group

c. Ester group

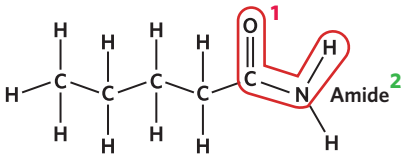
18. **a.**



b.



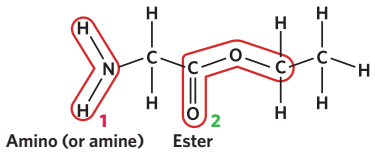
19. **a.**



I have circled the correct functional group.[1]

I have correctly named the functional group.[2]

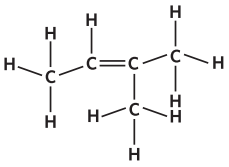
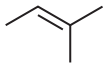
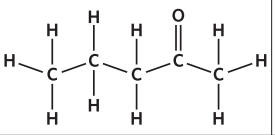
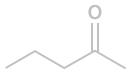
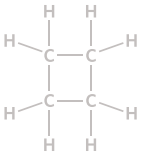
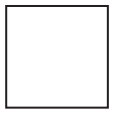
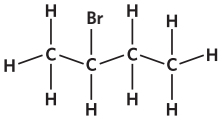
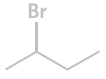
b.



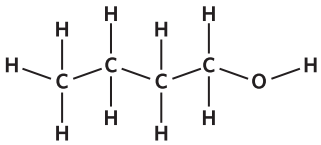
I have circled the correct functional groups.[1]

I have correctly named the functional groups.[2]

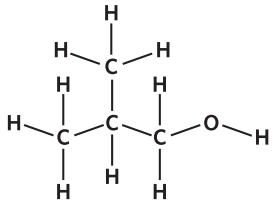
20.

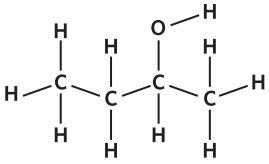
Semi-structural formula	Structural formula	Skeletal formula
$CH_3CHC(CH_3)CH_3$		
$CH_3CH_2CH_2COCH_3$		
$CH_2CH_2CH_2CH_2$		
$CH_3CHBrCH_2CH_3$		

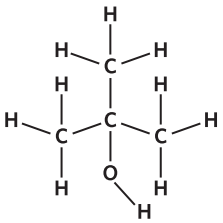
21. **a.**



Alternative answer:

- 

b. 

c. 

22. [Compared to longer bonds, shorter bonds are generally more stable and require more energy to break.[1]][Therefore, as the carbon-hydrogen bond is shorter than the carbon-nitrogen bond, the carbon-hydrogen bond is expected to have a higher bond energy.[2]]

✓ ✗ I have explained the relationship between bond length and bond energy.[1]

✓ ✗ I have identified that the carbon-hydrogen bond has a higher bond energy, referencing its length.[2]

Key science skills

23. a. Qualitative data

b. $CH_3(CH_2)_{20}CH_3$

FROM LESSON 12B

24. The partial charges in the halogen group

Alternative answer:

- All covalent bonds between atoms

FROM LESSON 12E

25. Skeletal formulas do not show hydrogen atoms bonded to carbon atoms, whereas structural formulas do. Removing these hydrogen atoms improves readability by simplifying the structure.

FROM LESSON 12E

Questions from multiple lessons

26. a. Renewable energy source

b. [The biobutanol molecule shown is a primary alcohol[1]][as the carbon atom to which the hydroxyl (−OH) group is bonded is only bonded to one other carbon atom.[2]]

✓ ✗ I have identified biobutanol as a primary alcohol.[1]

✓ ✗ I have identified the relationship between the bonding of the hydroxyl group to the alcohol type.[2]

c. 1 mol of C_4H_9OH can release 2676 kJ of energy. Therefore,

$$n(C_4H_9OH) \text{ used to produce 1033 kJ of energy} = \frac{1033 \text{ kJ}}{2676 \text{ kJ mol}^{-1}}$$

$n(C_4H_9OH)$ used to produce 1033 kJ of energy $= 0.38602$ mol

(1 MARK)

$n(C_4H_9OH) : n(O_2)$

$1 \quad : \quad 6$

$n(O_2) = 0.38602 \text{ mol} \times 6$

$n(O_2) = 2.3161$ mol (1 MARK)

$m(O_2) = n \times M$

$m(O_2) = 2.316 \text{ mol} \times 32.0 \text{ g mol}^{-1}$

$m(O_2) = 74.1$ g (1 MARK)

FROM LESSONS 1B & 2A

7B Naming and properties of organic compounds

Progress questions

1. A. The parent carbon chain contains three carbon atoms, resulting in the prefix 'prop-'. It also contains an amino group at the first carbon atom in the chain, giving the name 'propan-1-amine' (or '1-propanamine').

2. B. This molecule has five carbon atoms in the parent chain, resulting in the prefix 'pent-'. Carbon atoms 2 and 3 (counting from the right) are each only bonded to one hydrogen and two carbon atoms, indicating the presence of a double bond between these two carbon atoms. This double bond occurs at the second carbon, giving the name 'pent-2-ene' (or '2-pentene').

3. C. 2,4-dimethylpentane has the molecular formula C_7H_{16}. This is different form to the molecular formula of 2,2,4-trimethylpentane, is C_8H_{18}, so it is not a structural isomer.

4. C. These molecules experience hydrogen bonding due to the presence of the (O—H) bond. This is the strongest intermolecular force. Although covalent bonding is stronger than hydrogen bonding, covalent bonds form between atoms within a molecule rather than between adjacent molecules.

5. D. Compound 2 has a smaller surface area than compound 1, so experiences weaker dispersion forces between molecules. These weak intermolecular forces require less energy (heat) to be overcome, resulting in a lower boiling point.

6. D. Compound 2 is the most polar due to its three highly polar (O—H) bonds and would experience hydrogen bonding between its molecules. Compound 3 is the next most polar due to its singular (O—H) bond and would also experience (slightly less) hydrogen bonding between molecules. Compound 1 is a short-chain hydrocarbon, so it only experiences weak dispersion forces between its molecules. Viscosity increases with increasing strength of intermolecular forces between molecules.

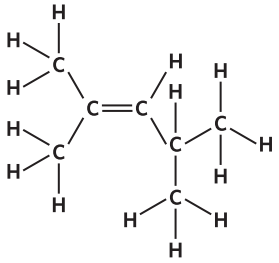
Deconstructed

7. C **8.** B

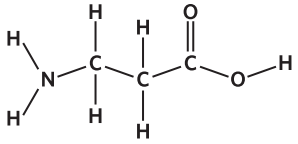
9. The parent carbon chain is eight carbon atoms long and contains two methyl groups at carbon atoms three and five. Therefore, its IUPAC name is 3,5-dimethyloctane.

Exam-style

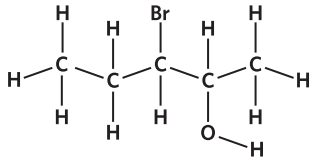
10. a.



b.



c.



11. This molecule is branched, which results in the molecules having a smaller surface area, meaning it experiences weaker dispersion forces between adjacent molecules.

12. a. propyl methanoate

b. 3,4-dimethylpent-1-ene

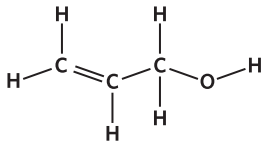
c. pentan-2,4-diol

d. 2,3-dibromobutane

e. 2-aminobutan-1-ol

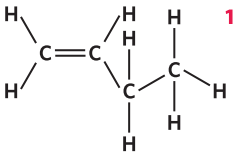
13. a. CH_3COCH_3 or $(CH_3)_2CO$

b.

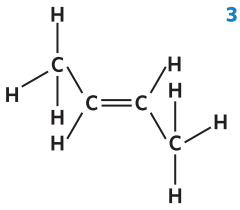


14. A. Prefixes are listed in alphabetical order, ignoring counting prefixes ('di', 'tri', 'tetra', etc.).

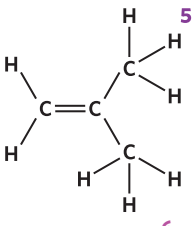
15.



But-1-ene [2]



But-2-ene [4]



Methylpropene [6]

- ✓ ✗ I have correctly drawn an isomer of C_4H_8. [1]
- ✓ ✗ I have correctly named the isomer drawn. [2]
- ✓ ✗ I have correctly drawn another isomer of C_4H_8. [3]
- ✓ ✗ I have correctly named the structure drawn. [4]
- ✓ ✗ I have correctly drawn another isomer of C_4H_8. [5]
- ✓ ✗ I have correctly named the structure drawn. [6]

16. [Due to the presence of hydroxyl groups and an aldehyde group, molecules of substance I experience hydrogen bonding and permanent dipole-dipole attraction in addition to dispersion forces.[1]][Molecule II is a hydrocarbon whose only functional group is a carbon-carbon double bond, so experiences only dispersion forces between molecules. Although molecule II has a relatively large surface area compared to molecule I,[2]] [these dispersion forces are still weaker than the strong hydrogen bonding between molecules of molecule I. As a result, the forces of attraction between molecules of compound I are stronger than in a sample of compound II, making molecule I more resistant to flow.[3]]

- ✓ ✗ I have identified the intermolecular forces experienced by molecule I. [1]
- ✓ ✗ I have identified the intermolecular forces experienced by molecule II. [2]
- ✓ ✗ I have compared the flow of both molecules I and II in relation to their intermolecular forces. [3]

17. A. Boiling points of organic compounds are related to the strengths of intermolecular forces between molecules. All three molecules have the same molar mass and similar surface area, so the contribution from dispersion forces will be similar for all. Compounds X and Y both experience hydrogen bonding (due to highly polar O—H bonds) and compound Y also experiences dipole-dipole interactions due to its C=O bond. However, compound Z only experiences dipole-dipole attraction in addition to dispersion forces, which is weaker than hydrogen bonding. Therefore, compound Z would have the lowest boiling point.

18. D. C_2HF_3 is an unsaturated organic compound with a parent carbon chain containing two carbon atoms. Whichever carbon atom the hydrogen is connected to will be the second carbon atom, resulting in the IUPAC name 1,1,2-trifluoroethene.

Key science skills

19. a. Dispose of it in a suitable, labelled waste container.

b. The time it takes for 20 mL of liquid to be delivered from the burette

Alternative answer:

- Viscosity

c. i. The extent of opening of the burette tap

Alternative answers:

- Initial level of liquid in the burette
- Heat loss during transfer of samples from water to burette
- Initial flow rate from the burette
- Number of carbon atoms in soybean biodiesel and petrodiesel

ii. [Differences in the extent of opening of the burette tap would affect the flow rate of the liquid.[1]][If the burette tap is not fully open, the time taken to deliver 20 mL will be higher, leading to a lower experimentally determined viscosity.[2]]

I have explained the impact of the uncontrolled variable on flow rate.[1]

I have identified the impact on the independent variable.[2]

Alternative answers:

- If the liquids in each test start from different heights in the burette, there will be different initial flow rates. The higher the starting level, the lower the time taken to collect 20 mL, leading to results of lower viscosity.
- The flow rate of the two fuels is affected by the size of the molecules in the liquid, since larger molecular size increases viscosity and hence the time taken to deliver 20 mL, since the flow rate will be lower. Using the same number of carbon atoms in both liquids ensures that students can compare the effect of temperature on the viscosity of the liquids.

d. [The time taken for delivery of 20 mL of soybean biodiesel is greater at all temperatures,[1]][so the viscosity of soybean biodiesel is higher than the viscosity of petrodiesel.]

I have identified that the results for biodiesel are higher at all temperatures.[1]

I have concluded that soybean biodiesel is more viscous than petrodiesel.[2]

e. i. As temperature increases, the viscosity/time decreases.

ii. Viscosity at 30 °C for petrodiesel is higher than expected. The higher-than-expected time to deliver 20 mL could be due to the temperature of the petrodiesel being lower than 30 °C, increasing the time to deliver 20 mL.

Alternative answers:

- Burette tap not being opened as much as for the other temperatures
- Initial level of petrodiesel being lower than for the other temperatures

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

20. a. Hydroxyl group

b. [Tertiary alcohol.[1]][The hydroxyl group is attached to a carbon atom connected to three alkyl groups.[2]]

I have identified the type of alcohol shown in the structure.[1]

I have explained my answer.[2]

c. 3,5-dimethylhexan-3-ol

FROM LESSON 7A

21. B. Octan-1-ol and propan-1-ol are part of the same homologous series. However, octanol has a longer carbon chain, meaning its molecules have greater surface area and hence more dispersion forces. This results in a higher boiling point since more thermal energy is required to overcome these intermolecular forces.

FROM LESSONS 7A & 2B

22. C. Biodiesel molecules (fatty acid methyl esters) are polar and larger than petrol molecules (long straight-chain hydrocarbons), and so they have the strongest intermolecular attractions, and hence the highest viscosity. Whilst ethanol molecules are polar and experience hydrogen bonding, they are also much smaller than petrol molecules. This means that the overall attraction is the lowest of all four options, resulting in the lowest viscosity.

FROM LESSONS 1A & 1B

Chapter 7 review

Multiple Choice

1. B. Alkanes are saturated hydrocarbons, meaning they have the general formula C_nH_{2n+2} and all carbon-carbon bonds are single bonds.

2. B. The parent carbon chain is six carbon atoms long. There is a chlorine atom at the third carbon and a carbon-carbon double bond (alkene functional group) at the second carbon.

3. D. Skeletal formulas show all carbon atoms as vertices and ends of bonds and do not show carbon-hydrogen bonds. The structure contains 5 carbon atoms ($M = 12.0$ g mol^{-1}), 10 hydrogen atoms ($M = 1.0$ g mol^{-1}), and one oxygen atom ($M = 16.0$ g mol^{-1}). This molecule is a ketone (C=O bond occurs within the carbon chain).

4. C. The parent carbon chain is six carbon atoms long and has methyl groups at carbon atoms 3 and 4.

5. C. Structures I and IV both show 2,5-dimethylhexane.

6. D. Petrodiesel molecules only experience weak dispersion forces between molecules. Biodiesel molecules contain a polar C=O bond, resulting in dipole-dipole attractions between molecules and a higher boiling point (and viscosity).

7. B. Methyl propanoate, ethyl ethanoate, and propyl methanoate are all unbranched esters that share this molecular formula.

8. D. If there appear to be two options of names for an organic compound, the functional group with the highest priority (the suffix) receives the lower number.

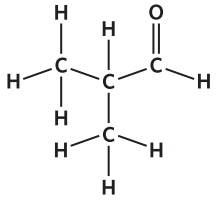
9. A. The parent carbon chain is 4 carbon atoms long. The hydroxyl group is connected to the first carbon, and the amino group is connected to the third carbon. According to IUPAC nomenclature, hydroxyl functional groups are a higher priority than amino functional groups, so the hydroxyl group forms the suffix.

10. A. Bond strength increases with increasing difference in electronegativity between atoms and decreasing bond length.

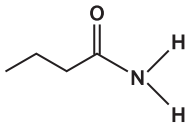
Short answer

11. a. Ethanol

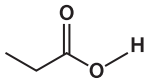
b. $HCOO(CH_2)_2CH_3$

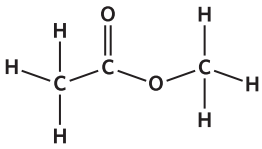
c. 

d. Aldehydes

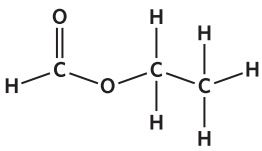
e. 

f. propan-2-ol or 2-propanol

12. a. 

b. i. 

Alternative answer:



ii. methyl ethanoate

Alternative answer:

- ethyl methanoate (name of structure in question 12bi alternative answer only)

13. [Unsaturated molecules contain one or more double bonds between carbon atoms.[1]][This is true for molecule B.[2]]

I have defined an unsaturated molecule.[1]

I have identified the unsaturated molecule.[2]

b. [Both molecules experience hydrogen bonding due to their O–H bond, and dipole-dipole attractions due to their C=O bond, in addition to dispersion forces.[1]][However, molecule B contains carbon-carbon double bonds and kinks in the carbon chain that reduce its surface area and decrease the strength of its dispersion forces, since molecules are unable to pack closely together.[2]][The weaker intermolecular forces between molecules of sample B mean that it is expected to have the lower boiling point.[3]]

I have discussed the intermolecular forces experienced by each molecule.[1]

I have discussed the relative strengths of these intermolecular forces.[2]

I have identified the sample expected to have the lower boiling point.[3]

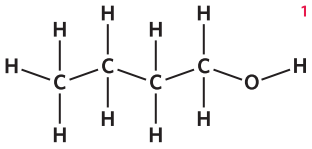
14. 4,5-diethyloctan-2,2-diamine

15. [Linoleic acid is expected to have a lower melting point.[1]][Although oleic and linoleic acid contain the same number of carbon atoms, linoleic acid contains an additional carbon-carbon double bond.[2]][This reduces the surface area of the molecule and, adds kinks to the chain that prevent close packing, reducing the strength of dispersion forces between molecules.[3]]

I have identified that linoleic acid is expected to have the lower melting point.[1]

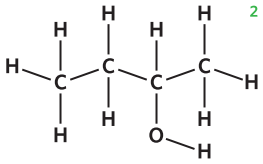
I have compared the relative number of C=C bonds in each molecule.[2]

I have explained why the additional carbon-carbon double bond results in a lower melting point.[3]

16. 

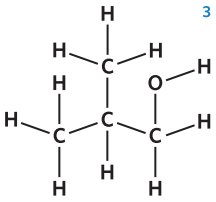
1

Primary alcohol



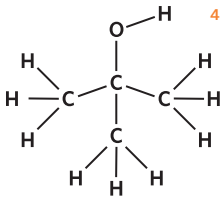
2

Secondary alcohol



3

Primary alcohol



4

Tertiary alcohol

I have drawn and classified an isomer of $C_4H_{11}OH$.[1]

I have drawn and classified another isomer of $C_4H_{11}OH$.[2]

I have drawn and classified another isomer of $C_4H_{11}OH$.[3]

I have drawn and classified another isomer of $C_4H_{11}OH$.[4]

17. [Although cyclohexane (C_6H_{12}) and benzene (C_6H_6) contain the same number of carbon atoms and are both hydrocarbons, which only experience dispersion forces between molecules,[1]][benzene's three carbon-carbon double bonds (and six less hydrogen atoms) reduce its surface area, decreasing the strength of its dispersion forces.[2]][Species that experience weaker intermolecular forces have lower melting points. Therefore, benzene is expected to have the lower melting point (5.5 °C), and cyclohexane is expected to have the higher melting point (6.5 °C).[3]]

I have identified the intermolecular force between molecules of cyclohexane and benzene.[1]

I have explained how carbon-carbon double bonds affect the strength of benzene's dispersion forces.[2]

I have identified the boiling points of cyclohexane and benzene.[3]

18. a. [At colder temperatures, the molecules do not have enough energy to disrupt the intermolecular forces between biodiesel molecules to allow the fuel to flow.[1]][This results in an increase in viscosity, making it more difficult for the fuel to flow through the fuel line.[2]]

- ✓ ✗ I have identified the relationship between temperature and strength of intermolecular forces.[1]
- ✓ ✗ I have identified the effect on viscosity with reference to the flow of the fuel.[2]

b. [Petrodiesel's non-polar hydrocarbon molecules are held together by weak dispersion forces.[1]][Biodiesel is a fuel consisting of molecules that contain a polar ester functional group, meaning its molecules are held together by both dispersion forces and stronger dipole-dipole interactions.[2]] [Therefore, the attractive forces between biodiesel molecules require more thermal energy to overcome, resulting in a higher boiling point.[3]]

- ✓ ✗ I have identified the type of intermolecular forces between petrodiesel molecules.[1]
- ✓ ✗ I have identified the types of intermolecular bonds present in biodiesel and their relative strengths.[2]
- ✓ ✗ I have explained why biodiesel has the higher boiling point.[3]

Key science skills

19. a. Boiling point

b. Improperly calibrated thermometer

c. [As both structures are alkanes, adjacent molecules are held together by dispersion forces. However, compared to structure 2, structure 1 has a larger surface area and less branching. This results in stronger dispersion forces between the molecules of structure 1, which require more thermal energy to overcome.[1]] [Therefore, it is expected that the higher boiling point (31.1 °C) belongs to structure 1, and the lower (10.2 °C) to structure 2.[2]]

- ✓ ✗ I have explained the intermolecular forces experienced by each molecule.[1]
- ✓ ✗ I have correctly assigned each molecule to its boiling point by referencing the results.[2]

FROM LESSONS 12B & 12D

20. a. [A: Primary amides. These experience hydrogen bonding (N—H), dipole-dipole attraction (C=O), and dispersion forces.[1]] [B: Carboxylic acids. These experience hydrogen bonding (O—H), dipole-dipole attraction (C=O), and dispersion forces.[2]] [C: Primary alcohols. These experience hydrogen bonding (O—H) and dispersion forces.[3]][D: Alkanes. These experience dispersion force only.[4]]

- ✓ ✗ I have classified homologous series A and stated the intermolecular forces it experiences.[1]
- ✓ ✗ I have classified homologous series B and stated the intermolecular forces it experiences.[2]
- ✓ ✗ I have classified homologous series C and stated the intermolecular forces it experiences.[3]
- ✓ ✗ I have classified homologous series D and stated the intermolecular forces it experiences.[4]

b. [As alkyl chain length increases, boiling point increases.[1]] [This is due to increased strength of dispersion forces between adjacent molecules as the surface area of molecules increases.[2]]

- ✓ ✗ I have identified the trend in boiling point within homologous series.[1]
- ✓ ✗ I have explained this trend with reference to intermolecular forces.[2]

FROM LESSON 12C

8A Types of organic reactions

Progress questions

1. D. Overall, a haloalkane reacts with ammonia to produce an amine and an ammonium salt.

2. C. Haloalkanes can react with ammonia to produce an amine, or with sodium hydroxide to produce an alcohol.

3. A. Alkenes undergo addition reactions, which form only one product.

4. D. Synthesis of a primary amine cannot be done via a single-step addition reaction.

5. A. $CH_3CH_2CHCH_2 + Cl_2 \rightarrow CH_3CH_2CHClCH_2Cl$; 1,2-dichlorobutane is formed as the chlorin atoms are added to carbon atoms one and two.

6. B. When esters are formed, water is also a product.

7. A. The reaction of methanoic acid and methanol in the presence of an acid catalyst to produce methyl methanoate and water is a condensation (esterification) reaction.

8. C. Methyl comes from the carboxylic acid, and the propanoate comes from the primary alcohol.

9. B. Oxygen is added to the alcohol, and the gain of oxygen is one of the definitions of oxidation.

10. A. In order for oxidising agents to remove electrons from other species, $H^+(aq)$ or $OH^-(aq)$ ions must be present.

11. D. The hydroxyl, $-OH$, group is assigned carbon number one according to IUPAC naming convention. Since only primary alcohols can be oxidised to acids, the methyl group is on carbon number three.

12. B. The lowest number (2 vs 3) when locating the chlorine atom is used.

13. A. All alkenes undergo addition reactions, and can then be oxidised (e.g. ethene to ethanol, and then to ethanoic acid).

14. C. Triglycerides react with methanol to form fatty acid methyl esters (biodiesel) and glycerol.

15. B. Specific enzymes are required to break down fats in the body.

16. D. This is a transesterification reaction used to form biodiesel (fatty acid methyl esters).

17. C. Amino acids join an amino group ($-NH_2$) from one amino acid to the carboxyl group ($-COOH$) of another amino acid.

Deconstructed

18. B

19. A

20. [Reactant A: IV,[1]][Reactant B: VII,[2]][Reagent(s) X: III,[3]] [Reagent(s) Y: I,[4]][Reagent(s) Z: II.[5]]

- ✓ ✗ I have deduced that propan-1-ol (a three carbon primary alcohol) can be synthesised from propene (IV).[1]
- ✓ ✗ I have deduced that ethanoic acid can be synthesised from ethanol (VII).[2]
- ✓ ✗ I have given the number for the reagent(s) (III) required to convert an alkene into an alcohol.[3]
- ✓ ✗ I have given the number for the reagent(s) (I) required to convert a primary alcohol into a carboxylic acid.[4]
- ✓ ✗ I have given the number for the reagent(s) (II) required to carry out an esterification reaction.[5]

Exam-style

21. C. Plants build triglycerides and humans break them down.

22. C. Reaction of the alkene with HCl produces chloroalkanes. While there are two possible products, compound K must be 1-chlorobutane since the final product is butan-1-ol. A chloroalkane is normally converted to an alcohol by reaction with $OH^-(aq)$. However, the same outcome can be achieved, albeit slowly, by reaction with H_2O.

23. A. Given that the double bond is between carbon atoms one and two, the iodine will bond to these two carbon atoms.

24. B. The triglyceride will hydrolyse to 3 × fatty acids and a glycerol molecule.

25. **a.** Carboxyl and amino functional groups attached to the same C atom

Alternative answers:

- $-COOH$ and $-NH_2$ attached to the same C atom
- Amino ($-NH_2$) functional group attached to second C atom

b. Hydrolysis reaction

c. Condensation

26. **a.** Addition

b. $CH_3CHClCH_2CH_3$

Alternative answer:

- $CH_3CH_2CHClCH_3$

c. NaOH or KOH. Any soluble metal hydroxide is accepted. It should be noted that H_2O is not a sufficiently powerful addition reagent for this reaction to proceed at an appreciable rate.

Alternative answer:

- OH^-

d. i. $H_2SO_4(l)$ or $H_3PO_4(l)$

(aq) is not accepted – must be concentrated

Alternative answer:

- Concentrated H_2SO_4 (sulfuric acid) or concentrated H_3PO_4 (phosphoric acid)

ii. $[CH_3CH_2CH_2OH + HCOOH^{[1]}][\rightarrow HCOOCH_2CH_2CH_3 + H_2O^{[2]}]$

- ✓ ✗ I have written the correct formulas of the reactants.[1]
- ✓ ✗ I have written the correct formulas of the products.[2]

iii. Propyl methanoate

Key science skills

27. a. $C_{12}H_{22}O_{11}(s) + H_2O(l) \rightarrow 2C_6H_{12}O_6(aq)$

b. Enzymes

c. [Volume or concentration of the enzyme.[1]]
[Volume or concentration of the sucrose solution.[2]]

✓ ✗ I have identified a variable.[1]

✓ ✗ I have identified a second variable.[2]

Alternative answers:

- Volume or concentration of indicator
- Person deciding when the colour change occurs

d. Temperature

e. [No, as when the temperature is doubled, the time taken does not halve. Therefore, there is not a directly proportional relationship between temperature and rate of hydrolysis.[1]]
[For a change from 10 °C to 20 °C, the time taken decreases from 40 s to 25 s. If this relationship were directly proportional, the time taken for the reaction to occur at 20 °C would be 20 s (half of 40 s).[2]]

✓ ✗ I have explained my reasoning.[1]

✓ ✗ I have justified my reasoning using the results and calculations.[2]

f. As the temperature increases (from 10 °C to 40 °C) the rate of hydrolysis increases (the time to change colour decreases).

g. Use narrower increments between temperature changes (e.g. 5 °C, 10 °C, 15 °C etc.)

h. This ensures that only one variable is influencing the time taken to change colour.

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

28. a. [Reduction: $Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \rightarrow 2Cr^{3+}(aq) + 7H_2O(l)$[1]]
[Oxidation: $CH_3CH_2CH_2CH_2CH_2OH(aq) \rightarrow 2H^+(aq) + 2e^- + CH_3CH_2CH_2CH_2CHO(aq)$[2]]

✓ ✗ I have written a balanced reduction half-equation.[1]

✓ ✗ I have written a balanced oxidation half-equation.[2]

b. The student could limit the amount of oxidising agent.

FROM LESSONS 3A & 3B

29. a. $n(C_{12}H_{22}O_{11}) = \frac{m}{M}$

$n(C_{12}H_{22}O_{11}) = \frac{1.50 \times 10^3 \text{ kg}}{342.0 \text{ g mol}^{-1}}$

$n(C_{12}H_{22}O_{11}) = 4.385 \text{ mol}$ (1 MARK)

$n(C_{12}H_{22}O_{11}) : n(C_2H_5OH)$

1 : 4

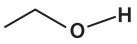
$n(C_2H_5OH) = 4 \times 4.385 \text{ mol}$

$n(C_2H_5OH) = 17.54 \text{ mol}$ (1 MARK)

$m(C_2H_5OH) = n \times M$

$m(C_2H_5OH) = 17.54 \text{ mol} \times 46.0 \text{ g mol}^{-1}$

$m(C_2H_5OH) = 8.07 \times 10^2 \text{ g}$ (1 MARK)

b. i. 

ii. Addition and oxidation reaction

iii. H_3PO_4 (l)

Alternative answer:

- Concentrated H_3PO_4

FROM LESSON 2A

8B Sustainability of the production of chemicals

Progress questions

1. A. $(0.80 \times 0.70) \times 100\% = 56\%$

2. C. Atom economy $= \frac{M(\text{ethanol})}{M(\text{reactants})} \times 100\%$

The atom economies of the four reactions are:

A. 100%

B. $\frac{92.0 \text{ g mol}^{-1}}{180.0 \text{ g mol}^{-1}} \times 100\% = 51.1\%$

C. $\frac{46.0 \text{ g mol}^{-1}}{104.5 \text{ g mol}^{-1}} \times 100\% = 44.0\%$

D. $\frac{46.0 \text{ g mol}^{-1}}{92.0 \text{ g mol}^{-1}} \times 100\% = 50.0\%$

3. A. Most plastics are derived from crude oil.

4. A. First generation biofuels require food crops to be replaced with fuel crops.

5. C. If the rate of reaction is faster, less energy will need to be used as the effect of the catalyst is much greater than the effect of an increase in temperature or pressure, which require more energy to maintain.

6. D. Polymers that are made of naturally occurring molecules (proteins and polysaccharides) will break down into naturally occurring monomers (amino acids and sugars).

Deconstructed

7. B **8.** A **9.** B

10. % atom economy $= \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$

% atom economy $= \left(\frac{88.0 \text{ g mol}^{-1}}{150.9 \text{ g mol}^{-1} + 40.0 \text{ g mol}^{-1}}\right) \times 100\%$

% atom economy = 46.1%

Alternative answer:

- % atom economy $= \left(\frac{88.0 \text{ g mol}^{-1}}{88.0 \text{ g mol}^{-1} + 102.9 \text{ g mol}^{-1}}\right) \times 100\%$
- % atom economy = 46.1%

Exam-style

11. A. Transition metal compounds are often used as catalysts to help improve the sustainability of chemical reactions.

12. B. Many processes involved in the creation of bioplastics – planting, maintenance, harvesting, and transportation – require energy, and greenhouse gases are generally released in the production of this energy.

13. C. Biopolymers are made of proteins and polysaccharides, which can be broken down via hydrolysis reactions.

14. C. $\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$40.0\% = \frac{10.5\text{ g}}{\text{theoretical yield}} \times 100\%$

$\text{Theoretical yield} = \frac{10.5\text{ g}}{0.400}$

$\text{Theoretical yield} = 26.25\text{ g}$

$n(\text{CaO}) = \frac{m}{M}$

$n(\text{CaO}) = \frac{26.25\text{ g}}{56.1\text{ g mol}^{-1}}$

$n(\text{CaO}) = 0.4679\text{ mol}$

Ratio of 1:1

$n(\text{CaCO}_3) = n(\text{CaO})$

$m(\text{CaCO}_3) = M \times n$

$m(\text{CaCO}_3) = 100.1\text{ g mol}^{-1} \times 0.4679\text{ mol}$

$m(\text{CaCO}_3) = 46.8\text{ g}$

Key science skills

15. a. 3 steps (6 conventional – 3 green)

b. [Less waste is produced[1]][and less energy is consumed.[2]]

✓ ✗ I have given an example of an advantage.[1]

✓ ✗ I have given an example of another advantage.[2]

c. i. By using the ethanoic acid in another process

ii. A mass of 60.0 g mol^{-1} accounts for $100\% - 77.44\% = 22.56\%$ (1 MARK)

$\text{molar mass per percent} = \frac{60.0\text{ g mol}^{-1}}{22.56\%}$

$\text{molar mass per percent} = 2.659\text{ g mol}^{-1}$

$M(\text{ibuprofen}) = \text{molar mass per percent}\ \text{atom economy}$

$M(\text{ibuprofen}) = 2.659\text{ g mol}^{-1} \times \frac{77.44\%}{100\%}$

$M(\text{ibuprofen}) = 206\text{ g mol}^{-1}$ (1 MARK)

Alternative answer:

A mass of 60.0 g mol^{-1} accounts for $100\% - 77.44\% = 22.56\%$ (1 MARK)

$\frac{22.56\%}{77.44\%} = \frac{60.0\text{ g mol}^{-1}}{M(\text{ibuprofen})}$ (1 MARK)

$M(\text{ibuprofen}) = 60.0\text{ g mol}^{-1} \times \frac{77.44\%}{22.56\%}$

$M(\text{ibuprofen}) = 206\text{ g mol}^{-1}$ (1 MARK)

d. Given that the actual molar mass of ibuprofen is 206.29 g mol^{-1} the percentage values are very accurate to three significant figures.

FROM LESSON 12D

16. a. Bioethanol and ethanol are the exact same molecule; the only differences are their source and production processes.

b. [$C_6H_{12}O_6(aq)$[1]][$\rightarrow 2C_2H_5OH(aq) + 2CO_2(g)$[2]]

✓ ✗ I have given the correct formulas of products and reactants.[1]

✓ ✗ I have balanced the equation and included state symbols.[2]

c. $\%\text{ atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$

$\text{Fermentation} = \left(\frac{2 \times 46.0\text{ g mol}^{-1}}{180.0\text{ g mol}^{-1}}\right) \times 100\%$

Fermentation % atom economy = 51.1% (1 MARK)

All reactants are converted into desired products during the hydration of ethene, as it is an addition reaction.

Therefore,

Hydration % atom economy = 100% (1 MARK)

Therefore, the hydration of ethene has a greater atom economy than the fermentation of glucose. (1 MARK)

d. [Renewable feedstocks[1]][and less energy consumption.[2]]

✓ ✗ I have identified a green principle.[1]

✓ ✗ I have identified a second green principle.[2]

FROM LESSONS 1B & 8A

Chapter 8 review

Multiple choice

1. C. Some catalysts are very expensive and difficult to produce, creating a lot of waste (e.g. titanium).

2. B. Biomass is made from plants, which can be replaced within a relatively short period of time.

3. D. Biopolymers are made up of proteins or polysaccharides, which have bonds (amide and ether, respectively) that are readily hydrolysed.

4. D. Esters are produced using an alcohol and carboxylic acid, and so when they are hydrolysed they produce an alcohol and a carboxylic acid.

5. D. The chlorine atoms will be added to where the double bond was initially located: across carbon numbers 2 and 3.

6. C. This is an addition reaction because Cl_2 has been added across the C=C double bond, but it is also a redox reaction. The oxidation state of Cl decreases from 0 in $Cl_2(g)$ to −1 in CH_2ClCH_2Cl. In CH_2CH_2, the oxidation state of each H is +1, which means that the oxidation state of each C is −2. In CH_2ClCH_2Cl, the oxidation states are H: +1, Cl: −1, C: −1. The oxidation state of C has increased (from −2 to −1) and the oxidation state of Cl has decreased from 0 to −1, so the reaction between CH_2CH_2 and Cl_2 is a redox reaction as well as an addition reaction.

7. A. $\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

Esterification reactions produce an ester and water, and the methanoic acid and methanol react in a 1:1 ratio.

$HCOOH + CH_3OH \rightarrow HCOOCH_3 + H_2O$

Methanoic acid is therefore the limiting reactant, so only 1 mole of the methyl methanoate (60.0 g mol^{-1}) can be produced.

8. C. The functional groups of ibuprofen (carboxyl, −COOH) and lysine (amine, $-NH_2$) can undergo a condensation reaction to form an amide (peptide) bond. The amine group that forms part of the amide bond must come from the number 2 carbon and not the side chain (A is incorrect as the amine group involved in the bond is from the side chain).

9. C. $\%\text{ atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$

Option A: Propene combustion does not produce any organic molecules.

Option B: $C_3H_8 + I_2 \rightarrow C_3H_7I + HI$

$$\%\text{ atom economy} = \frac{169.9\text{ g mol}^{-1}}{44.0\text{ g mol}^{-1} + 253.8\text{ g mol}^{-1}} \times 100\%$$

$\%\text{ atom economy} = 57.1\%$

Option C: $C_3H_6 + Br_2 \rightarrow C_3H_6Br_2$

$$\%\text{ atom economy} = \frac{201.8\text{ g mol}^{-1}}{42.0\text{ g mol}^{-1} + 159.8\text{ g mol}^{-1}} \times 100\%$$

$\%\text{ atom economy} = 100\%$

Option D: $CH_3CH_2Br + NaOH \rightarrow CH_3CH_2OH + NaBr$

$$\%\text{ atom economy} = \frac{46.0\text{ g mol}^{-1}}{109\text{ g mol}^{-1} + 40.0\text{ g mol}^{-1}} \times 100\%$$

$\%\text{ atom economy} = 30.9\%$

10. B. Glycerol is one of the products of the hydrolysis of triglycerides; the other product(s) are fatty acids.

Hydrolysis of tripalmitin:

$C_{51}H_{98}O_6 + 3H_2O \rightarrow 3C_{15}H_{31}COOH + C_3H_8O_3$

$n = \frac{m}{M}$

$$n(C_3H_8O_3) = \frac{65.0\text{ g}}{92.0\text{ g mol}^{-1}}$$

$n(C_3H_8O_3) = 0.7065$ mol

$n(C_3H_8O_3) : n(H_2O)$

1 : 3

$n(H_2O) = 3 \times 0.7065$

$n(H_2O) = 2.11956$ mol

$m = n \times M$

$m(H_2O) = 2.11956\text{ mol} \times 18.0\text{ g mol}^{-1}$

$m(H_2O) = 38.2$ g

Short answer

11. [As a condensation polymer, the molecule is able to undergo hydrolysis.[1]][This results in the breakdown of the polymer back into its monomers, and an increased rate of biodegradation.[2]] [Biodegradation is related to the implementation of a circular economy, as biodegraded condensation monomers can be used in the replenishment of renewable polymer-forming reactants.[3]]

✓ ✗	I have identified the chemical reaction that makes the molecule biodegradable.[1]
✓ ✗	I have explained the chemistry of this chemical reaction.[2]
✓ ✗	I have related this to the implementation of a circular economy.[3]

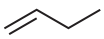
12. a. $650C_6H_{12}O_6(aq) \rightarrow C_{3900}H_{6502}O_{3251}(aq) + 649H_2O(l)$

b. Condensation (polymerisation)

c. Glycosidic linkage, ether

d. $M(C_{3900}H_{6502}O_{3251}) = (3900 \times 12.0\text{ g mol}^{-1}) + (6502 \times 1.0\text{ g mol}^{-1}) + (3251 \times 16.0\text{ g mol}^{-1})$

$M(C_{3900}H_{6502}O_{3251}) = 105\,318\text{ g mol}^{-1}$

13. a. i. 

ii. Butan-1-ol or 1-butanol

Alternative answer:

- Butan-2-ol or 2-butanol

iii. $CH_3CH_2CH_2COOH$ or $CH_3CH_2CH_2CHO$

Alternative answer:

- $CH_3CH_2COCH_3$

b. i. $CH_3CH_2CH_2Cl(g) + 2NH_3(g) \rightarrow CH_3CH_2CH_2NH_2(g) + NH_4Cl(g)$

ii. Propan-1-amine or 1-propanamine

iii. Substitution

iv. $\%\text{ atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of reactants used}} \times 100\%$

$$\%\text{ atom economy} = \frac{59.0\text{ g mol}^{-1}}{78.5\text{ g mol}^{-1} + 34.0\text{ g mol}^{-1}} \times 100\%$$

(1 MARK)

$\%\text{ atom economy} = 52.4\%$ (1 MARK)

14. a. i. F. The major components of biodiesels are fatty acid methyl esters.

ii. E. Triglycerides react with methanol (in alkali) to make biodiesel and glycerol.

iii. E and D. Triglycerides hydrolyse into three fatty acids and glycerol.

iv. H. Starch is a type of carbohydrate made from glucose monomers joined by ether bonds (glycosidic links).

v. B and C. Monosaccharide monomers can polymerise through a condensation reaction by ether bonds.

vi. G. Unsaturated means containing a double bond, so unsaturated molecules contain fewer hydrogen atoms than if they were saturated.

b. [Hydrolysis.[1]] [A specific enzyme.[2]]

- ✓ ✗ I have named the type of reaction.[1]
- ✓ ✗ I have given the necessary reagent for the reaction to occur.[2]

15. a. Addition

b. CH_3CHICH_3

c. NaOH or KOH or OH^-

d. i. Concentrated or liquid (l) H_2SO_4 or H_3PO_4

ii. Esterification or condensation

iii. [$CH_3OH + CH_3CH_2COOH \rightarrow CH_3CH_2COOCH_3 + H_2O$[1]] [Methyl propanoate[2]]

- ✓ ✗ I have written the equation for the reaction.[1]
- ✓ ✗ I have written the name of the organic molecule formed.[2]

Key science skills

16. a. [Triglycerides could come from non-food crops,[1]] [which would reduce competition with food production.[2]]

- ✓ ✗ I have suggested how triglycerides could be made greener.[1]
- ✓ ✗ I have explained why my suggestion is greener.[2]

b. [A less corrosive source of hydroxide (such as magnesium hydroxide) could be used instead of potassium hydroxide.[1]] [This would reduce the risk of harm to the environment and improve efficiency.[2]]

- ✓ ✗ I have suggested how the reactant could be made greener.[1]
- ✓ ✗ I have explained why my suggestion is greener.[2]

c. [Produce methanol made from renewable resources (biomass fermentation)[1]] [rather than from crude oil, as this is more sustainable.[2]]

- ✓ ✗ I have suggested how the reactant could be made greener.[1]
- ✓ ✗ I have explained why my suggestion is greener.[2]

d. [Use the glycerol in another process,[1]] [as this would increase atom economy and reduce waste products.[2]]

- ✓ ✗ I have suggested how the glycerol could be made greener.[1]
- ✓ ✗ I have explained why my suggestion is greener.[2]

FROM LESSON 12B

17. a. The biodiesel life cycle requires approximately four times less fossil fuel energy (311 kJ) than the petrodiesel life cycle (1200 kJ).

b. The production process of biodiesel requires approximately 6% of the fossil fuel energy required for that of petrodiesel.

$$\frac{66\text{ kJ}}{1112\text{ kJ}} \times 100\% \approx 6\%$$

FROM LESSON 12C

9A Testing for functional groups

Progress questions

1. C. Hexene is an unsaturated molecule that decolourises bromine water.

2. A. $KMnO_4: 1 + (4 \times -2) + 7 = 0$

   $MnO_2: (2 \times -2) + 4 = 0$

   The manganese ion has gained three electrons (become less positive) and is hence reduced.

3. D. Many of the reactions involve oxidising agents as alcohols are readily oxidised.

4. C. Tertiary alcohols are very unreactive and resist oxidation.

5. B. Mineral and inorganic acids do not contain carbon.

6. C. The carboxyl group is a combination of two functional groups, the hydroxyl (−OH) and carbonyl (−C=O) groups.

7. C. Most organic acids do not have an aroma.

Deconstructed

8. C

9. D

10. [The compound contains a carbon-carbon double bond due to the colour change from light orange/ brown to colourless,[1]][and a hydroxyl group from an alcohol as a cloudy solution formed from a colourless solution.[2]]

- ✓ ✗ I have identified the presence of a carbon-carbon double bond.[1]
- ✓ ✗ I have identified the presence of a hydroxyl group from an alcohol.[2]

Exam-style

11. a. [To confirm the presence of a carboxyl group, use the acid-base indicator test using phenolphthalein.[1]][To confirm the presence of a carbon-carbon double bond, use bromine water.[2]]

- ✓ ✗ I have given an appropriate test for an identified functional group.[1]
- ✓ ✗ I have given an appropriate test for a different identified functional group.[2]

Alternative answers:

- Reaction with metal carbonates or metal bicarbonates to show the presence of a carboxyl group
- Esterification with an alcohol and acid to produce a sweet smelling ester
- Acidified potassium permanganate test to show unsaturation

b. Benzoic acid

c. [It is possible to only show the presence of the two functional groups,[1]][as they are qualitative tests that cannot be used to determine the overall structure.[2]]

- ✓ ✗ I have stated that only the two functional groups can be identified.[1]
- ✓ ✗ I have stated the limitations of qualitative tests.[2]

Key science skills

12. a. [Cyclohexene and pent-3-en-oic acid are predicted to both give a positive test with bromine water as they contain a carbon-carbon double bond,[1]][but if sodium carbonate solution is added to both, only pent-3-en-oic acid is expected to react, producing bubbles.[2]][When added to acidified potassium dichromate, propan-1-ol should turn from orange to green as it contains a hydroxyl group.[3]]

- ✓ ✗ I have explained how cyclohexene and pent-3-en-oic acid can be identified due to their carbon-carbon double bond.[1]
- ✓ ✗ I have explained how cyclohexene and pent-3-en-oic acid can be differentiated due to the reaction of pent-3-en-oic acid with sodium carbonate.[2]
- ✓ ✗ I have explained how propan-1-ol can be identified.[3]

b. [Refer to the Safety Data Sheets (SDS or MSDS) or a prepared approved risk assessment document for each of the chemicals.[1]][Follow all suggested storage, handling and personal protective equipment guidelines given in the material safety data sheets.[2]]

- ✓ ✗ I have stated where safety guidelines can be found.[1]
- ✓ ✗ I discussed how the student should adhere to the relevant safety guidelines.[2]

FROM LESSON 12B

Questions from multiple lessons

13. a. [$CH_3CH_2CH_2CH_2OH(l) + [O]$[1]][$\rightarrow CH_3CH_2CH_2CHO(aq) + H_2O(l)$[2]][Oxidation.[3]]

- ✓ ✗ I have written the reactants in the equation and state symbols.[1]
- ✓ ✗ I have written the products in the equation and state symbols.[2]
- ✓ ✗ I have classified the type of reaction.[3]

b. Butan-1-ol is classified as a primary alcohol as the carbon bonded to the hydroxyl group is only bonded to one other carbon atom.

c. Secondary alcohols cannot be oxidised to an aldehyde, the required compound for the formation of a carboxylic acid. They are instead oxidised to a ketone.

d. [React the carboxylic acid with a primary alcohol[1]] [in the presence of heat[2]] [and concentrated sulfuric acid[3]] [to produce an ester and water.[4]]

- ✓ ✗ I have identified what to react with the carboxylic acid.[1]
- ✓ ✗ I have identified the reaction condition required.[2]
- ✓ ✗ I have identified the catalyst required.[3]
- ✓ ✗ I have identified the products.[4]

FROM LESSONS 7A & 8A

9B Analysis of consumer products

Progress questions

1. B. Melting point is the temperature at which the forces of attraction between molecules or ions are overcome and a change in state occurs from solid to liquid, which is a physical change.

2. D. Only purity can be accurately assessed using melting point; all the other properties would require further information.

3. B. The melting point of an impure compound is less than that of a pure compound because the impurities disrupt and weaken the overall molecular or lattice structure. This means that less energy is required to overcome the forces of attraction in the solid, causing it to melt.

4. B. Boiling point is the temperature at which the forces of attraction between molecules or ions are overcome and a physical change in state occurs from solid to liquid.

5. D. If a known mixture were distilled, the different components (fractions) that make up the mixture could be identified by their boiling points and therefore be verified as present.

6. A. The presence of impurities in a liquid will increase the boiling point of a compound by introducing additional intermolecular forces or disrupting the crystal lattice, and by lowering the vapour pressure.

Deconstructed

7. B **8.** D

9. D. Option A: As Y boils after X, Y is less volatile.

Option B: It is not possible to determine molar mass from the order in which the fractions boil.

Option C: As X boiled first, it has the lowest melting point.

Option D: As fraction Z distilled last, it must have the highest boiling point, which is due to it having the strongest forces of attraction in the liquid.

Exam-style

10. C. A substance's temperature remains constant during phase changes due to its particles absorbing the supplied heat energy (which prevents it from increasing further) and instead using it to overcome the attractive forces in the compound.

11. D. Many substances can have similar melting points; for example, mandelic and benzoic acid both have a melting point of 121 °C.

12. B. Fractional distillation is the best method for verifying components that have similar boiling points. Option B has a difference of only 2 K.

13. [A sharply defined melting point can be used to determine if the tablet is pure by comparing it to its known melting temperature, whereas a broad range of melting points can indicate that the tablet is contaminated.[1]] [The purity of the tablet can be verified using (fractional) distillation by comparing the experimental boiling point of the tablet with its known value.[2]] [If the tablet contains a contaminant then it will contain two or more different distillates (fractions) that boil at different temperature[3]] [and this will allow the contaminant to be separated.[4]]

- ✓ ✗ I have explained how melting point can determine purity.[1]
- ✓ ✗ I have explained how purity can be analysed using (fractional) distillation.[2]
- ✓ ✗ I have explained that two different boiling temperatures would occur.[3]
- ✓ ✗ I have explained how the product and contaminant can be separated.[4]

Key science skills

14. a. [Boiling point is the most appropriate physical property to test,[1]] [as compound B has already melted at room temperature.[2]] [Appropriate methods of separation would be fractional distillation or repeated simple distillation.[3]]

- ✓ ✗ I have identified the most appropriate physical property.[1]
- ✓ ✗ I have justified why the physical property is appropriate.[2]
- ✓ ✗ I have identified an appropriate method.[3]

b. [Given that both compounds A and B will have already become a distillate above 110 °C,[1]] [only compound C would remain in the flask as it has a boiling point of 1413 °C.[2]]

- ✓ ✗ I have identified the states of compounds A and B at 110 °C.[1]
- ✓ ✗ I have explained why compound C would remain in the flask.[2]

c. [Compound A has a melting point of −1 °C and boiling point of 101 °C, and will therefore be a liquid at 85 °C.[1]]
[Compound B has a melting point of −114 °C and boiling point of 78.4 °C, and will therefore be a gas at 85 °C.[2]]
[Compound A has a melting point of 801 °C and boiling point of 1413 °C, and will therefore be a solid at 85 °C.[3]]

- ✓ ✗ I have identified and explained the physical state of compound A.[1]
- ✓ ✗ I have identified and explained the physical state of compound B.[2]
- ✓ ✗ I have identified and explained the physical state of compound C.[3]

d. [Water.[1]][Given that pure water normally boils at 100 °C and melts at 0 °C,[2]][it is possible that the water has impurities as the melting point has been lowered.[3]]

- ✓ ✗ I have suggested a possible identity for compound A.[1]
- ✓ ✗ I have discussed the temperatures at which water changes physical states.[2]
- ✓ ✗ I have explained why the melting point has decreased.[3]

FROM LESSON 12C

Questions from multiple lessons

15. a. $n(\text{Q}) = \frac{V}{V_m}$

$n(\text{Q}) = \frac{124 \times 10^{-3}\ \text{L}}{24.8\ \text{L mol}^{-1}}$

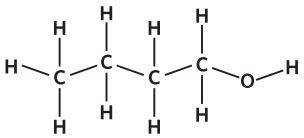
$n(\text{Q}) = 5.00 \times 10^{-3}\ \text{mol}$ (1 MARK)

$M(\text{Q}) = \frac{m}{n}$

$M(\text{Q}) = \frac{0.371\ \text{g}}{15.00 \times 10^{-3}\ \text{mol}}$

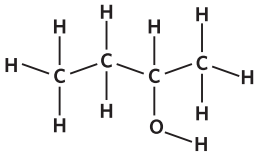
$M(\text{Q}) = 74.2\ \text{g mol}^{-1}$ (1 MARK)

b. i.



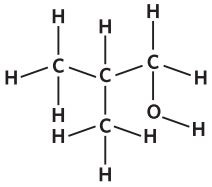
(1 MARK)

Butan-1-ol (1 MARK)



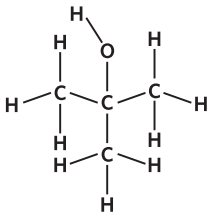
(1 MARK)

Butan-2-ol (1 MARK)



(1 MARK)

2-methylpropan-1-ol or methylpropan-1-ol (1 MARK)



(1 MARK)

2-methylpropan-2-ol or methylpropan-2-ol (1 MARK)

ii. [T: butan-1-ol or 2-methylpropan-1-ol.[1]]
[M: 2-methylpropan-2-ol.2[2]]

- ✓ ✗ I have given the name of compound T.[1]
- ✓ ✗ I have given the name of compound M.[2]

FROM LESSONS 2A, 7B & 8A

9C Volumetric analysis of redox reactions

Progress questions

1. B. The burette dispenses solution incrementally into the conical flask.

2. D. Concentration is found by dividing n (mol) by V (volume in L).

3. A. As c is being multiplied on the right, when it is moved to the left, n is divided by c.

4. C. Concordant titres are values that fall within a range of 0.10 mL (17.65 mL/17.65 mL/17.60 mL).

5. C. The end point indicates the approximate point at which the stoichiometric ratios of the reactants are met, noted by the colour change of the indicator.

6. B. The equivalence point is found at the halfway point of the vertical part of the curve.

7. A. The dichromate ion, $Cr_2O_7^{2-}(aq)$, is very dangerous to humans (e.g. toxic if swallowed, harmful in contact with skin, fatal if inhaled and causes severe skin burns and eye damage).

8. B. Unsaturated fats and oils contain carbon-carbon double bonds that iodine monochloride can react with by an addition reaction.

Deconstructed

9. D **10.** A

11. C. Option A: Adding less water to the conical flask has no effect on V(titre), since $n(I_2)$ required to react with vitamin C is not affected.

Option B: If the $c(I_2)$ was recorded as higher than the true value, the calculated $n(I_2)$ in the titre, the calculated n(vitamin C) in 5.0 mL graph juice, and consequently the calculated c(vitamin C) will be overestimated.

Option C: If the initial volume in the burette is read as higher than the calculated V(titre) (i.e. final volume), the initial volume will be lower than the true value so the calculated $n(I_2)$ in the titre, the calculated n(vitamin C) in 5.0 mL grapefruit juice, and consequently the calculated c(vitamin C) will be underestimated.

Option D: If the recorded V(grapefruit juice) was higher than the true value, this would have an effect on the titration; the calculated c(vitamin C) will be overestimated.

Exam-style

12. D. Pipettes have a resolution of 0.01 mL and should be used as they are the most accurate available.

13. D. Colourless $Mn^{2+}(aq)$ to purple when $Mn^{7+}(aq)$ is in excess.

14. D. Pipettes and burettes should be rinsed with the solution being transferred from them. Flasks should be rinsed with distilled water. Only the conical flask was rinsed correctly.

15. $n(KMnO_4) = c \times V$

$n(KMnO_4) = 0.0200\ M \times (21.70 \times 10^{-3}\ L)$

$n(KMnO_4) = 4.34 \times 10^{-4}\ mol$ (1 MARK)

$n(KMnO_4) : n(H_2C_2O_4)$

2 : 5

$n(H_2C_2O_4) = \frac{5}{2} \times (4.34 \times 10^{-4}\ mol)$

$n(H_2C_2O_4) = 1.085 \times 10^{-3}\ mol$ (1 MARK)

$c(H_2C_2O_4) = (1.08 \times 10^{-3}\ mol) \times \frac{1000}{20.00\ mL}$

$c(H_2C_2O_4) = 5.43 \times 10^{-2}\ mol\ L^{-1}$ (1 MARK)

16. a. $IV = \frac{(V_{blank} - V_{sample}) \times 0.10\ M \times 126.9\ g\ mol^{-1}}{mass\ of\ sample\ (g)}$

$IV = \frac{1.50\ mL \times 0.10\ M \times 126.9\ g\ mol^{-1}}{0.25\ g}$ (1 MARK)

$IV = 76$ (1 MARK)

b. With a value of 76 it would be considered to have a high proportion of unsaturated molecules and to be a liquid at room temperature.

17. $n_{(reducing\ agent)} = c \times V$

$n_{(reducing\ agent)} = 0.01600\ L \times 1.0\ mol\ L^{-1}$

$n_{(reducing\ agent)} = 0.01600\ mol$

$n_{(diluted\ oxidising\ agent)} = n_{(reducing\ agent)}$

$n_{(diluted\ oxidising\ agent)} = 0.01600\ mol$ (1 MARK)

$c_{(diluted\ oxidising\ agent)} = \frac{n}{V}$

$c_{(diluted\ oxidising\ agent)} = \frac{0.01600\ mol}{0.02000\ L}$

$c_{(diluted\ oxidising\ agent)} = 0.8000\ mol\ L^{-1}$ (1 MARK)

$c_{(undiluted\ oxidising\ agent)} = dilution\ factor \times c_{(diluted\ oxidising\ agent)}$

$c_{(undiluted\ oxidising\ agent)} = 10 \times 0.800\ mol\ L^{-1}$

$c_{(undiluted\ oxidising\ agent)} = 8.0\ mol\ L^{-1}$ (1 MARK)

Key science skills

18. a. $n(MnO_4^-) = c \times V$

$n(MnO_4^-) = 1.00\ mol\ L^{-1} \times \left(\frac{25.00}{1000}\right) L$

$n(MnO_4^-) = 0.025\ mol$ (1 MARK)

$n(C_2O_4^{2-}) = c \times V$

$n(C_2O_4^{2-}) = 1.00\ mol\ L^{-1} \times \left(\frac{20.0}{1000}\right) L$

$n(C_2O_4^{2-}) = 0.020\ mol$ (1 MARK)

$n(C_2O_4^{2-}) < \frac{5}{2} \times n(MnO_4^-)$

Therefore $C_2O_4^{2-}$ is the limiting reagent. (1 MARK)

In the equation

$n(MnO_4^-) : n(C_2O_4^{2-})$

2 : 5

$n(C_2O_4^{2-}\text{required}) = 0.025\ mol \times \frac{5}{2}$

$n(C_2O_4^{2-}\text{required}) = 0.0625\ mol$ (1 MARK)

$V_{total} = \frac{n}{c}$

$V_{total} = \frac{0.0625\ mol}{1.00\ mol\ L^{-1}}$

$V_{total} = 0.625\ L$

$V_{total} = 0.625\ L \times 1000$

$V_{total} = 62.5\ mL$ (1 MARK)

$V_{to\ add} = 62.5\ mL - 20.00\ mL\ (original\ volume)$

$V_{to\ add} = 42.5\ mL$ (1 MARK)

b. [Washing the burette with water results in residual water being left in the burette.[1]][Due to water diluting the solution, a greater volume would need to be delivered to reach the endpoint (same amount of permanganate in mole is delivered).[2]][As a greater volume of permanganate is required than without dilution, the calculated concentration of ethanedioic acid is expected to be greater than the true concentration.[3]]

✓ ✗ I have identified the impact of washing the burette with water.[1]

✓ ✗ I have described the effect of washing with water on the volume of potassium permanganate delivered by the burette.[2]

✓ ✗ I have described the effect of washing with water on the accuracy of the calculated concentration of ethanedioic acid.[3]

c. [The conical flask can have residual water because it is not the concentration of the unknown solution that is important in the flask, but the amount of solute.[1]][Therefore, the conical flask cannot be washed with the unknown solution because residual ethanedioic acid could be left, leading to the calculated concentration of ethanedioic acid being greater than the actual concentration.[2]]

✓ ✗ I have explained why water can be used to wash the conical flask.[1]

✓ ✗ I have explained why ethanedioic acid cannot be used to wash the conical flask.[2]

d. [Gloves and eye protection should be worn.[1]][The lab should have easily accessible dilute sodium thiosulfate that can be used to remove the deep purple colour[2]][The broken glass should be safely cleaned up and disposed of into a specific broken glass container using a dustpan and brush.[3]]

I have identified one safety precaution that could be taken.[1]

I have identified a second safety precaution that could be taken.[2]

I have identified a third safety precaution that could be taken.[3]

FROM LESSONS 12B & 12D

Questions from multiple lessons

19. a. $[MnO_4^-(aq) + 8H^+(aq) + 5e^-$ [1]$][\rightarrow Mn^{2+}(aq) + 4H_2O(l)$ [2]$]$

Alternative answer:

- $MnO_4^-(aq) + 8H_3O^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 12H_2O(l)$

b. $\frac{21.95\text{ mL} + 22.00\text{ mL} + 22.05\text{ mL}}{3} = 22.00\text{ mL}$

(20.25 mL was not concordant with the other three titres)

c. $n(MnO_4^-) = c \times V$

$n(MnO_4^-) = 0.0400\text{ M} \times (22.00 \times 10^{-3}\text{ L})$

$n(MnO_4^-) = 8.80 \times 10^{-4}\text{ mol}$

d. $n(MnO_4^-) : n(Fe^{2+})$

1 : 5

$n(Fe^{2+})$ in 20.00 mL aliquot $= \frac{5}{1} \times (8.80 \times 10^{-4}\text{ mol})$

$n(Fe^{2+})$ in 20.00 mL aliquot $= 4.40 \times 10^{-3}$ mol (1 MARK)

$n(Fe^{2+})$ in 250 mL flask $= (4.40 \times 10^{-3}\text{ mol}) \times \frac{250.0\text{ mL}}{20.00\text{ mL}}$

$n(Fe^{2+})$ in 250 mL flask $= 5.50 \times 10^{-2}$ mol (1 MARK)

e. $n(Fe)$ in 80.50 g alloy $= 5.50 \times 10^{-2}$ mol

$m = n \times M$

$m(Fe)$ in 80.50 g alloy $= 5.50 \times 10^{-2}\text{ mol} \times 55.8\text{ g mol}^{-1}$

$m(Fe) = 3.069$ g (1 MARK)

$\%\text{ Fe in alloy} = \frac{3.069\text{ g}}{80.50\text{ g}} \times 100\%$

% Fe in alloy = 3.81% (1 MARK)

3 (sig. figs) (1 MARK)

FROM LESSON 3B

Chapter 9 review

Multiple choice

1. A. The Lucas test is a test for hydroxyl groups in alcohols not the hydroxyl group found in a carboxylic acid.

2. A. If impurities are present, then the recorded melting point will be lower (termed 'melting point depression') and over a broader range when compared to its known pure melting temperature.

3. D. All factors that affect the amount of intermolecular forces that can occur between molecules will affect the boiling point.

4. B. Pure substances have a sharply defined melting point (within a very small temperature range of 1–2 °C), while impure substances have a broader melting temperature.

5. B. Fractional distillation utilises a fractionating column which allows gas to be constantly condensed and boiled many times which improves the purity of the distillate. Simple distillation must be repeated many times as it does not use a fractionating column.

6. C. Sodium thiosulfate can only be oxidised and is therefore a reducing agent used in redox titrations. Sodium thiosulfate remains colourless when it is oxidised.

7. C. At a higher altitude the atmospheric pressure decreases which therefore results in less energy (in the form of heat – measured in °C) being required to overcome the forces of attraction between liquid water molecules.

8. B. Everest boiling point ≈ 72 °C

Kosciuszko boiling point ≈ 93 °C

Difference = 21 °C

$\text{Difference} = \frac{21}{72} \times 100\%$

Difference = 30%

9. B. $n(I_2) = c \times V$

$n(I_2) = 0.015\text{ mol L}^{-1} \times \left(\frac{25.0}{1000}\right)\text{ L}$

$n(I_2) = 0.000375$ mol or 3.75×10^{-4} mol

$n(Na_2S_2O_3) = c \times V$

$n(Na_2S_2O_3) = 0.00600\text{ mol L}^{-1} \times \left(\frac{20.0}{1000}\right)\text{ L}$

$n(Na_2S_2O_3) = 0.00012$ mol or 1.2×10^{-4} mol

$n(I_2)$ is in excess.

Given that $Na_2S_2O_3(aq)$ reacts with I_2 in a ratio of 2 : 1,

Amount of $I_2(aq)$ reacted $= \frac{1}{2} \times n(Na_2S_2O_3)$

Amount of $I_2(aq)$ reacted $= 0.600 \times 10^{-4}$ mol of $I_2(aq)$

Excess reagent is $I_2(aq)$
= Initial amount of $I_2(aq)$ − Reacted amount of $I_2(aq)$

Excess reagent is $I_2(aq) = (3.75 \times 10^{-4}\text{ mol}) - (0.600 \times 10^{-4}\text{ mol})$

Excess reagent is $I_2(aq) = 3.15 \times 10^{-4}$ mol

10. C. $\text{IV} = \frac{(V_{blank} - V_{sample}) \times 0.10\text{ M} \times 126.9\text{ g mol}^{-1}}{\text{mass of sample (g)}}$

$\text{IV} = \frac{1.10\text{ mL} \times 0.10\text{ M} \times 126.9\text{ g mol}^{-1}}{0.30\text{ g}}$

IV = 47

Short answer

11. a. Iodine is reduced to iodide ions ($0 \rightarrow -1$) and is therefore the oxidising agent.

b. Freshly prepared starch solution (this should be added near the end point once it is known, as this helps see the colour change)

c. $n = c \times V$

$n(I_2) = 0.100\text{ M} \times \left(\frac{14.95}{1000}\right)\text{ L}$

$n(I_2) = 0.001495$ mol

d. $n(I_2) : n(SO_2)$

$1 : 1$

$n(SO_2) = n(I_2)$

$n(SO_2) = 0.001495 \text{ mol}$ (1 MARK)

$c = \frac{n}{V}$

$c(SO_2) = \frac{0.001495 \text{ mol}}{0.02000 \text{ L}}$

$c(SO_2) = 0.07475 \text{ mol L}^{-1}$ (1 MARK)

e. Dilution factor $= \frac{\text{final volume}}{\text{initial volume}}$

Dilution factor $= \frac{100.0 \text{ mL}}{25.0 \text{ mL}}$

Dilution factor $= 4$

Wine was diluted to the ratio of 1 : 4 – dilution factor is 4

f. $c_1V_1 = c_2V_2$

$c_1 = \frac{c_2V_2}{V_1}$

$c(SO_2)_{\text{original}} = 0.07475 \text{ mol L}^{-1} \times \frac{100.0 \text{ mL}}{25.0 \text{ mL}}$

$c(SO_2)_{\text{original}} = 0.299 \text{ M (or mol L}^{-1})$

12. a. $n = c \times V$

$n(MnO_4^-) = 0.500 \text{ M} \times \left(\frac{18.95}{1000}\right) \text{L}$

$n(MnO_4^-) = 0.009475 \text{ mol}$ (1 MARK)

$n(MnO_4^-) : n(C_2O_4^{2-})$

$2 : 5$

$n(C_2O_4^{2-}) = n(MnO_4^-) \times \frac{5}{2}$

$n(C_2O_4^{2-}) = 0.009475 \text{ mol} \times \frac{5}{2}$

$n(C_2O_4^{2-}) = 0.02368 \text{ mol in } 25.00 \text{ mL}$ (1 MARK)

$c(C_2O_4^{2-}) = \frac{n}{V}$

$c(C_2O_4^{2-}) = \frac{0.02368 \text{ mol}}{0.02500 \text{ L}}$

$c(C_2O_4^{2-}) = 9.48 \times 10^{-1} \text{ M}$ (1 MARK)

b. $M(H_2C_2O_4) = (1.0 \text{ g mol}^{-1} \times 2) + (12.0 \text{ g mol}^{-1} \times 2) + (16.0 \text{ g mol}^{-1} \times 4)$

$M(H_2C_2O_4) = 90.0 \text{ g mol}^{-1}$ (1 MARK)

$m(H_2C_2O_4) = 90.0 \text{ g mol}^{-1} \times 1.1 \text{ mol}$

$m(H_2C_2O_4) = 99 \text{ g}$ (1 MARK)

13. a. $[MnO_4^-(aq) + 5e^- + 8H^+(aq)^1][\rightarrow Mn^{2+}(aq) + 4H_2O(l)^2]$

✓ ✗ I have included the correct balanced reactants including states.[1]

✓ ✗ I have included the correct balanced products including states.[2]

b. $n(MnO_4^-) = c \times V$

$n(MnO_4^-) = 0.500 \text{ M} \times \left(\frac{14.55}{1000}\right) \text{L}$

$n(MnO_4^-) = 0.007275 \text{ mol}$ (1 MARK)

Fe^{2+} is oxidised according to the redox half-equation

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$

$n(MnO_4^-) : n(Fe^{2+})$

$1 : 5$

$n(Fe^{2+}) = 0.007275 \text{ mol} \times 5$

$n(Fe^{2+}) = 0.036375 \text{ mol}$ (1 MARK)

$c(FeSO_4) = \frac{n}{V}$

$c(FeSO_4) = \frac{0.036375 \text{ mol}}{0.0200 \text{ L}}$

$c(FeSO_4) = 1.81875 \text{ mol L}^{-1}$ (1 MARK)

c. 25.0 mL : 250.0 mL

$1 : 10$

Dilution factor of 10 (1 MARK)

$c(FeSO_4)$ in original sample $= 1.81875 \text{ mol L}^{-1} \times 10$

$c(FeSO_4)$ in original sample $= 18.2 \text{ mol L}^{-1}$ (1 MARK)

14. a. [Lucas reagent and gentle heating,[1]][which is a mixture of concentrated hydrochloric acid and zinc chloride.[2]] [Only propan-1-ol will produce a positive test: colourless to cloudy; the others will remain colourless.[3]]

✓ ✗ I have stated the name of the test used.[1]

✓ ✗ I have included the chemicals required.[2]

✓ ✗ I have described the observations for all three liquids.[3]

b. [Pent-1-ene is the only compound that contains a carbon-carbon double bond and can undergo an addition reaction.[1]][Use bromine water test.[2]][$C_5H_{10}(l) + Br_2(aq) \rightarrow C_5H_{10}Br_2(aq)$.[3]][Only pent-1-ene will decolourise the light/brown orange solution.[4]]

✓ ✗ I have stated the type of reaction occurring.[1]

✓ ✗ I have stated the name of the test used.[2]

✓ ✗ I have included the correct balanced equation including states.[3]

✓ ✗ I have described the observations for all three liquids.[4]

c. [As cyclohexane does not have a functional group, it will therefore produce two negative tests; Lucas' reagent will remain colourless,[1]][and bromine water will remain light brown/orange.[2]]

✓ ✗ I have described the tests that could be used.[1]

✓ ✗ I have described the observations of the tests.[2]

d. [A primary alcohol and alkene will both give a positive result,[1]] [as they are both readily oxidised: primary alcohol → carboxylic acid and alkene → ketone and/or carboxylic acid.[2]]

- I have stated that both the alcohol and alkene will give positive results.[1]
- I have explained why both substances will give positive results.[2]

Key science skills

15. a. [$2MnO_4^-(aq) + 5H_2O_2(aq) + 6H^+(aq)$[1]][$\rightarrow 5O_2(g) + 2Mn^{2+}(aq) + 8H_2O(l)$[2]]

- I have included the correct balanced reactants including states.[1]
- I have included the correct balanced products including states.[2]

b. [An acid-base titration curve shows the change in pH of the analyte solution during the course of the titration reaction,[1]] [whereas redox titration curves show the E^0 changes throughout the reaction.[2]]

- I have identified the variable that is measured during an acid-base titration reaction.[1]
- I have identified the variable that is measured during a redox titration reaction.[2]

c. $M(KMnO_4) = 39.1\text{ g mol}^{-1} + 54.9\text{ g mol}^{-1} + (4 \times 16.0\text{ g mol}^{-1})$

$M(KMnO_4) = 158.0\text{ g mol}^{-1}$ (1 MARK)

$m(KMnO_4) = 1.50\text{ g in 1 L of solution}$

$n(KMnO_4) = \frac{m}{M}$

$n(KMnO_4) = \frac{1.50\text{ g}}{158.0\text{ g mol}^{-1}}$

$n(KMnO_4) = 0.0094936\text{ mol in 1 L of solution}$

$c(KMnO_4) = 0.0094936\text{ mol L}^{-1}$ (1 MARK)

In 12.00 mL of $KMnO_4$:

$n(KMnO_4) = c \times V$

$n(KMnO_4) = 0.0094936\text{ mol L}^{-1} \times \left(\frac{12.00}{1000}\right)\text{ L}$

$n(KMnO_4) = 0.00011392\text{ mol}$ (1 MARK)

$n(KMnO_4) : n(H_2O_2)$

$2 : 5$

$n(H_2O_2) = 0.00011392\text{ mol} \times \frac{5}{2}$

$n(H_2O_2) = 0.00028481\text{ mol in 20.00 mL}$ (1 MARK)

$c(H_2O_2) = \frac{n}{V}$

$c(H_2O_2) = \frac{0.00028481\text{ mol}}{0.02000\text{ L}}$

$c(H_2O_2) = 0.0142\text{ mol L}^{-1}$ (1 MARK)

d. [Wear gloves when handling hydrogen peroxide.[1]] [Wear safety glasses when handling hydrogen peroxide.[2]]

- I have identified a way to minimise burns.[1]
- I have identified a way to minimise eye damage.[2]

FROM LESSONS 12B, 12C & 12E

10A Mass spectrometry

Progress questions

1. A. The mass-to-charge ratio of the molecular ion can be used to determine the molecular mass of the original compound.

2. B. The molecular ion peak is generated by a positively charged form of the original molecule.

3. A. The molecular ion peak is produced by the form of the unfragmented molecule that has lost an electron.

4. D. The peak at $m/z = 58$ is caused by the molecular ion of propanone, which is $[CH_3COCH_3]^+$.

5. A. The relative mass of $[CH_3]^+$ is 15.0 g mol^{-1} and the charge on $[CH_3]^+$ is +1.

6. C. Mass spectrometry can be used to qualitatively determine the presence or absence of certain ions in a sample.

Deconstructed

7. C

8. D

9. $[NH_2CH_2]^+$ or $NH_2CH_2^+$

Exam-style

10. a. $[T]^+$, $[A]^+$, $[B]^+$

    b. i. Peak 1: $[B]^+$

    Peak 2: $[A]^+$

    Peak 3: $[T]^+$

    ii. Peak 2

11. a. $[CH_3CH_2]^+$ or $CH_3CH_2^+$ or $C_2H_5^+$ or $[C_2H_5]^+$

    b. [The peak at $m/z = 108$, which corresponds to the molecular ion $[C_2H_5{}^{79}Br]^+$ is slightly higher than peak at $m/z = 110$, which corresponds to the molecular ion $[C_2H_5{}^{81}Br^+]$.[1]] [Hence, the ^{79}Br isotope is slightly more abundant than the ^{81}Br isotope in this sample.[2]]

    ✓ ✗ I have identified that the peak caused by $[C_2H_5{}^{79}Br]^+$ is slightly higher than the peak caused by $[C_2H_5{}^{81}Br]^+$.[1]

    ✓ ✗ I have explained that the ^{79}Br isotope is slightly more abundant than the ^{81}Br isotope.[2]

Key science skills

12. a. [Whilst there is a distinct peak at 162 m/z, none of the other significant fragments for nicotine appear as peaks on the mass spectrum, so it is unlikely that nicotine was present in the blood sample.[1]] [There are distinct peaks at 188, 229 and 299 m/z, so it is likely that codeine was present in the blood sample.[2]] [There are also distinct peaks at 29, 31, 45 and 46 m/z, so it is likely that ethanol was also present in the blood sample.[3]]

    ✓ ✗ I have identified that nicotine is unlikely to be present in the blood sample.[1]

    ✓ ✗ I have identified that codeine is likely to be present in the blood sample.[2]

    ✓ ✗ I have identified that ethanol is likely to be present in the blood sample.[3]

    b. [By excluding individuals who ingest specific compounds, the effect of uncontrolled variables is reduced.[1]] [This enables Mossem to better isolate the impact of the medication being tested, thereby making the results of the studies more valid.[2]]

    ✓ ✗ I have explained that the screening process reduces the effect of uncontrolled variables.[1]

    ✓ ✗ I have linked this to the validity of the results.[2]

    c. [The exclusion of individuals who regularly ingest codeine could raise concerns about equitable access to clinical trials.[1]] [Codeine is a commonly used medication for pain relief and cough suppression, and excluding individuals who use it regularly may disproportionately affect certain populations, such as those with chronic pain or respiratory conditions.[2]] [Mossem should carefully consider the potential impact of exclusion criteria on different groups and strive for fair and inclusive participant selection.[3]]

    ✓ ✗ I have identified that equitable access to clinical trials is a key ethical consideration.[1]

    ✓ ✗ I have explained that excluding those who use codeine regularly may disproportionately affect certain populations.[2]

    ✓ ✗ I have explained that Mossem must strive for a fair and inclusive participant selection process.[3]

FROM LESSONS 12B, 12C & 12D

Questions from multiple lessons

13. From the mass spectrum, the molecular ion has a molecular mass of 58.0 g mol^{-1}. (1 MARK)

From the formula for an alkane, C_nH_{2n+2},

$M(\text{alkane}) = (12.0 \text{ g mol}^{-1} \times n) + (1.0 \text{ g mol}^{-1} \times (2n + 2))$

$58 \text{ g mol}^{-1} = 12.0n \text{ g mol}^{-1} + 2.0n \text{ g mol}^{-1} + 2.0 \text{ g mol}^{-1}$

$56 \text{ g mol}^{-1} = 14.0n \text{ g mol}^{-1}$

$$n = \frac{56.0 \text{ g mol}^{-1}}{14.0 \text{ g mol}^{-1}}$$

$n = 4$ (1 MARK)

Therefore, substituting $n = 4$ back into the formula for an unbranched alkane, we get the formula C_4H_{10}, which is the formula for butane. (1 MARK)

FROM LESSON 7A

10B Infrared spectroscopy

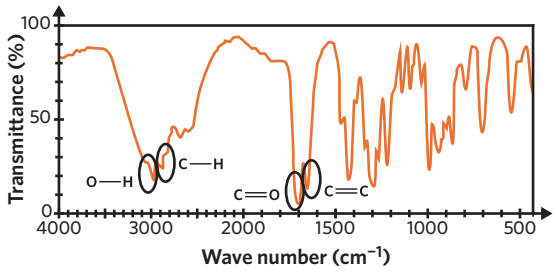
Progress questions

1. D. An IR spectrum can be used to determine the type of bonds present in an organic molecule.

2. C. In the IR spectrum of a carboxylic acid, there will be two prominent peaks: one at 1680–1740 cm^{-1}, C=O (acids) and one at 2500–3500 cm^{-1}, O–H (acids).

3. D. The spectrum has a distinct peak at approximately 1750 cm^{-1}, which could be due to the C=O bond in a ketone or ester. There is also a distinct peak at approximately 1250 cm^{-1}, which is likely to be caused by the C–O bond in an alcohol, ester or ether. Option C is the only formula that is consistent with this information.

4. C.



Deconstructed

5. A

6. D

7. C. The peak at 3300 cm^{-1} could be due to the O–H bond of an alcohol or the N–H bond of an amide or amine. The peak at 3000 cm^{-1} is due to the C–H bond. The peak at 1680 cm^{-1} could be due to either a C=C or C=O bond. The only compound that is consistent with these potential bond types is option C, an amide.

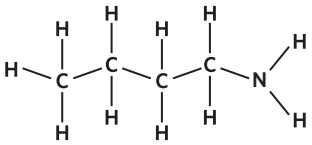
Exam-style

8. A. The peak at 3200–3500 cm^{-1} indicates either the O–H bond of an alcohol or an N–H bond and the peak at 1700 cm^{-1} indicates a C=O bond. This is consistent with the formula in option A.

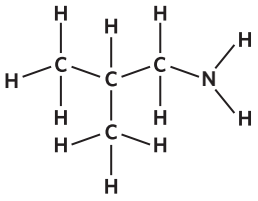
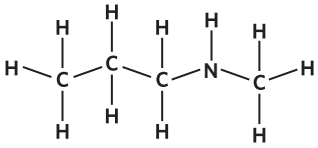
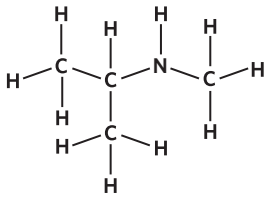
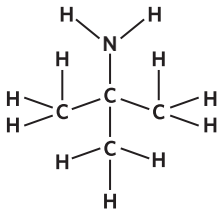
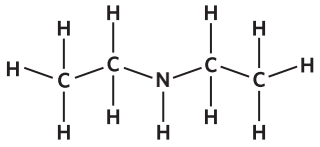
9. **a. i.** C–H

ii. N–H

b.



Alternative answers:

- 
- 
- 
- 
- 

Key science skills

10. [Compound P has no –O–H bond present, whilst the IR spectrum clearly shows the –O–H peak of an alcohol with an absorbance at approximately 3500 cm^{-1}. Hence, compound P is not consistent with the IR spectrum.[1]][Compound Q has an –O–H bond within a carboxyl (acid) functional group, whilst the IR spectrum clearly shows the –O–H peak of an alcohol with an absorbance at approximately 3500 cm^{-1}. Given there is no evidence of a broad peak between 2500 cm^{-1} and 3500 cm^{-1}, which is characteristic of the –O–H bond of an acid, compound Q is not consistent with the IR spectrum.[2]][Like compound P, compound S also has no –O–H bond present, whilst the IR spectrum clearly shows the –O–H peak of an alcohol with an absorbance at approximately 3500 cm^{-1}. Hence, compound S is not consistent with the IR spectrum.[3]][Compound R contains the –O–H bond of an alcohol, which is consistent with the IR spectrum. Compound R also contains the C=O bond of a ketone, which is consistent with the narrow peak at 1700 cm^{-1}.[4]]

✓ ✗ I have explained that compound P is not consistent with the IR spectrum.[1]

✓ ✗ I have explained that compound Q is not consistent with the IR spectrum.[2]

✓ ✗ I have explained that compound S is not consistent with the IR spectrum.[3]

✓ ✗ I have explained that compound R is consistent with the IR spectrum.[4]

FROM LESSONS 12C & 12E

Questions from multiple lessons

11. **a.** The peak at $m/z = 75$ could be due to the presence of a one-unit heavier isotope such as ^{13}C, ^{2}H or ^{17}O.

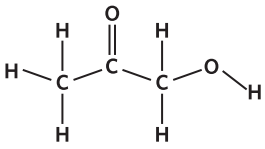
b. Based on the molecular ion peak at $m/z = 74$, the presence of only C, H and O in the compound, and the presence of either three or four carbon atoms in the compound, the only two possible molecular formulas are:

- $C_3H_6O_2$ (1 MARK)
- $C_4H_{10}O$ (1 MARK)

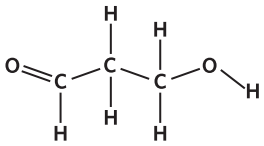
c. Peak A: −O−H (hydroxyl) (1 MARK)

Peak B: −C=O (carbonyl) (1 MARK)

d. The peak of an O−H bond in an acid ranges from 2500−3600 cm^{-1}, which overlaps the characteristic range of the peak caused by a C−H bond. Since the peak caused by a C−H bond is present in the spectrum, the leftmost peak must be caused instead by the O−H bond of an alcohol (3200−3600 cm^{-1}). From part c, there is also the C=O bond of an aldehyde or ketone present in the compound.



or



FROM LESSONS 7A & 10A

10C Low resolution carbon-13 nuclear magnetic resonance spectroscopy

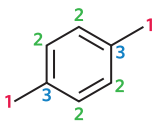
Progress questions

1. D. The number of peaks on a ^{13}C-NMR spectrum gives the number of non-equivalent carbon environments in an organic compound, which cannot be used to determine the number of carbon-13 nuclei in the compound.

2. A. According to the values given in the VCE Data Book, the two possible carbon environments that can produce the peak at 168 ppm are RCOOH (160–185 ppm) and RCOOR (165–175) ppm.

3. B. The number of peaks on a ^{13}C-NMR spectrum represents the number of non-equivalent carbon environments in a compound. The peak at 0 ppm is caused by the reference compound TMS and is therefore not included as one of the non-equivalent carbon environments.

4. A. The number of peaks in a ^{13}C-NMR spectrum corresponds to the number of non-equivalent carbon environments in a compound. The symmetry of the compound tells us that there are 3 non-equivalent carbon environments, and hence 3 peaks would be expected to appear in the ^{13}C-NMR spectrum.



Deconstructed

5. C **6.** B

7. [2-methylbutan-1-ol, 2-methylbutan-2-ol and 2,2-dimethylpropan-1-ol each have molar masses of 88 g mol^{-1}.[1]] [Only butan-1-ol and 2-methylbutan-2-ol have 4 non-equivalent carbon environments, meaning only they will show four distinct peaks on their ^{13}C-NMR spectra.[2]][Therefore, only compound III is consistent with the information given, and so 2-methylbutan-2-ol must be the compound represented in the ^{13}C-NMR spectrum.[3]]

- I have identified which of the compounds have the correct molar mass.[1]
- I have identified which of the compounds have the correct number of non-equivalent carbon environments.[2]
- I have identified the compound most likely to be the compound represented in the ^{13}C-NMR spectrum.[3]

Exam-style

8. [Diaminomethane has only 1 carbon environment, which is consistent with the ^{13}C-NMR spectrum given only 1 peak appears.[1]] [Additionally, the chemical shift value of the peak is approximately 46 ppm, which is consistent with the range of 35–70 ppm (from the VCE Data Book) for the R_3C-NH_2 carbon present in diaminomethane.[2]][Hence, the spectrum is consistent with the structure of diaminomethane.[3]]

- I have compared the number of carbon environments in diaminomethane to the number of peaks in the spectrum.[1]
- I have compared the chemical shift of the peak to the relevant chemical shift range given in the VCE Data Book.[2]
- I have identified whether the spectrum is consistent with the structure of diaminomethane.[3]

9. C. According to the ^{13}C-NMR spectrum, the compound contains three non-equivalent carbon environments. Only methylpropan-1-ol contains 3 non-equivalent carbon environments, whilst propane, methylbutane and methylpropan-2-ol each contain 2 non-equivalent carbon environments as they contain a line of symmetry. Therefore, the ^{13}C-NMR spectrum must correspond to methylpropan-1-ol.

10. a. TMS is a chemical used to provide a zero point for the horizontal axis on a ^{13}C-NMR spectrum, and serves as a common point of reference for chemical shifts.

b. [Methylpropan-2-ol has two non-equivalent carbon environments.[1]][The ^{13}C-NMR spectrum given shows three peaks, indicating there are three non-equivalent carbon environments in the unidentified molecule.[2]][Therefore, the compound the student proposes is not consistent with the ^{13}C-NMR data provided.[3]]

- I have identified the number of non-equivalent carbon environments in 2-methylpropan-2-ol.[1]
- I have identified the number of non-equivalent carbon environments in the unidentified molecule.[2]

I have determined whether the compound the student proposes is consistent with the spectrum provided.[3]

Key science skills

11. a. $CH_3CH_2CH_2OH$, $CH_3CH(OH)CH_3$

b. 1. Run the contents of the bottle through ^{13}C-NMR spectroscopy and identify the number of peaks shown in the ^{13}C-NMR spectrum produced. (1 MARK)

2. Identify the number of non-equivalent carbon environments in 1-propanol (3) and 2-propanol (2). (1 MARK)

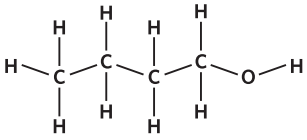
3. Compare the number of peaks shown to the number of non-equivalent carbon environments in each isomer of propanol. (1 MARK)

FROM LESSONS 12A & 12E

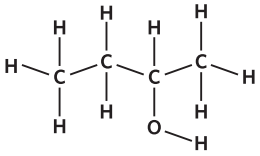
Questions from multiple lessons

12. a.

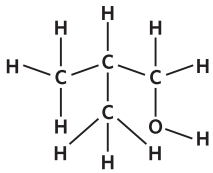
Alcohol I



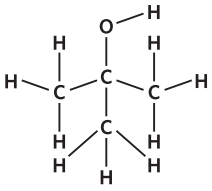
Alcohol II



Alcohol III



Alcohol IV



I have drawn a correct structure for an alcohol with the molecular formula of $C_4H_{10}O$.[1]

I have drawn a second correct structure for an alcohol with the molecular formula of $C_4H_{10}O$.[2]

I have drawn a third correct structure for an alcohol with the molecular formula of $C_4H_{10}O$.[3]

I have drawn a fourth correct structure for an alcohol with the molecular formula of $C_4H_{10}O$.[4]

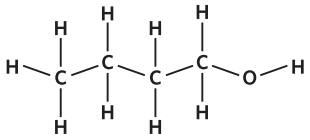
b. [From the ^{13}C-NMR spectrum, the compound contains 3 non-equivalent carbon environments.[1]][From the reaction with $Cr_2O_7^{2-}/H^+$ to produce a carboxylic acid, the compound must be a primary alcohol.[2]]

I have identified a piece of evidence from the ^{13}C-NMR spectrum information.[1]

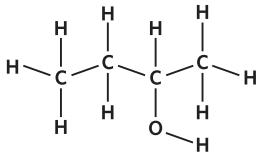
I have identified a piece of evidence from the reaction with $Cr_2O_7^{2-}/H^+$.[2]

c.

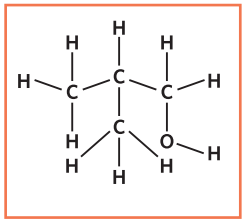
Alcohol I



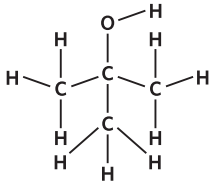
Alcohol II



Alcohol III



Alcohol IV



(1 MARK)

Methylpropan-1-ol (1 MARK)

FROM LESSONS 7A, 7B & 8A

10D Low & high resolution proton nuclear magnetic resonance spectroscopy

Progress questions

1. D. The integration curve provides information about the ratio of protons in different chemical environments within a molecule.

2. A. The peak splitting pattern observed in ^{1}H-NMR spectroscopy provides information about the number of neighbouring protons. Each set of equivalent neighbouring protons leads to a characteristic splitting pattern.

3. C. The n + 1 rule in ^{1}H-NMR spectroscopy is used to deduce the number and nature of non-equivalent proton environments based on the peak splitting patterns. It does not provide direct information about the chemical shift values.

4. A. A single peak in the ^{1}H-NMR spectrum indicates that the protons in the compound do not have any neighbouring protons. They are isolated and do not experience any splitting.

Deconstructed

5. B **6.** B

7. C. The spectrum indicates the presence of three non-equivalent proton environments, so options B and D can be ruled out as they have 4 and 2 respectively. The spectrum also shows the splitting patterns of a quartet, a triplet, and a singlet, which is consistent with both options A and C. However, the singlet appears at a chemical shift of 2.0 ppm which is only consistent with the CH_3–COOR group shown in option C.

Exam-style

8. D. The proton circled has 6 protons in its neighbouring proton environments, so 7 splits would appear in its set of peaks in a ^{1}H-NMR spectrum.

9. A. From the information provided, the compound must have 4 non-equivalent proton environments, and the number of protons in each type of environment must have a ratio of 3 : 2 : 2 : 1. This information is only consistent with option A, which contains 4 proton environments containing 3, 2, 1, and 2 protons respectively.

10. [There are 2 distinct peaks on the spectrum, so there are 2 non-equivalent proton environments present in the organic compound.[1]][The areas underneath the peak have a ratio of 17 : 51, which can be simplified to a ratio of 1 : 3, indicating that one proton environment contains 1 proton, and the other contains 3 protons.[2]][The peak with an area of 51 appears at a chemical shift of approximately 2.5 ppm, which aligns with the chemical shift ranges of an RC(O)C**H**$_3$ group (2.1–2.7 ppm), an R–O–**H** group (1–6 ppm), or an R–N**H**$_2$ group (1–5 ppm). However, since this proton environment contains 3 protons, the peak must be caused by an RC(O)C**H**$_3$ group.[3]][The peak with an area of 17 appears at a chemical shift of approximately 9.7 ppm, which aligns with the chemical shift ranges of an RCO**H** group (9.4–10.0 ppm) or an RCOO**H** group (9.0–13.0 ppm). However, since the compound contains only one oxygen atom, the peak must be caused by an RCO**H** group.[4]][Hence, the only organic compound that is consistent with all of this information is ethanal.[5]]

- I have identified the number of non-equivalent proton environments in the compound.[1]
- I have identified the number of protons in each proton environment.[2]
- I have identified the type of proton environment responsible for the peak with an area of 51.[3]
- I have identified the type of proton environment responsible for the peak with an area of 17.[4]
- I have deduced the name of the organic compound.[5]

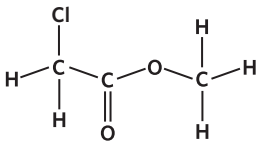
11. a. [There are two distinct peaks present on the spectrum, so there are non-equivalent proton environments present in the organic compound.[1]][Both peaks are singlets, so each non-equivalent proton environment has no neighbouring protons.[2]][The molecular formula contains 5 protons, so from the integration values, the ratio of the protons in the two environments is 2 : 3. In this case, the compound will have one hydrogen environment with 3 protons, and another with 2 protons.[3]]

- I have identified the number of non-equivalent proton environments present in the organic compound.[1]
- I have used the splitting patterns to identify the number of neighbouring protons .[2]
- I have used the integration values to determine the number of protons in the two environments.[3]

b. [The peak at 3.7 ppm must be caused by a proton environment containing 3 protons according to the ratio of the integration values.[1]][The only type of proton environment that is consistent with this is R–O–C**H**$_3$.[2]][The peak at 4.1 ppm must be caused by a proton environment containing 2 protons according to the ratio of the integration values. Additionally, the proton environment must contain a Cl atom as per the molecular formula given.[3]][The only type of proton environment that is consistent with this is R–C**H**$_2$–Cl.[4]]

- I have identified the number of protons in the proton environment responsible for the peak at 3.7 ppm.[1]
- I have identified the type of proton environment responsible for the peak at 3.7 ppm.[2]
- I have identified the number of protons and the presence of a Cl atom in the proton environment responsible for the peak at 4.1 ppm.[3]
- I have identified the type of environment responsible for the peak at 4.1 ppm.[4]

c.



Key science skills

12. a. [Jacob's assertion that low resolution proton NMR is 'easier to understand' is an example of anecdotal evidence,[1]][meaning their assertion is not scientifically valid as the ease of understanding is subjective.[2]]

- I have identified Jacob's assertion as an example of anecdotal evidence.[1]
- I have explained that Jacob's assertion is not scientifically valid.[2]

b. [Charbel's statement that high resolution proton NMR contains more useful information is correct,[1]][as high resolution proton NMR spectra show splitting patterns in addition to all the information provided by low resolution proton NMR spectra.[2]]

- I have identified that Charbel's statement is correct.[1]
- I have explained which additional information is provided by high resolution proton NMR spectra.[2]

FROM LESSONS 12A & 12C

13. a. [Proton NMR spectroscopy can be used to identify the presence or absence of functional groups or compounds in a sample[1]][by comparing the chemical shifts and splitting patterns of the peaks in the resulting spectrum with reference spectra of pure samples.[2]]

- I have identified a qualitative use for proton NMR spectroscopy.[1]
- I have described the technique for the qualitative use of proton NMR spectroscopy.[2]

b. [Proton NMR spectroscopy can be used to identify the number of non-equivalent proton environments in a compound, as well as the number of protons in each of those environments,[1]][by determining the number of peaks shown in a spectrum and the integration values of each of the peaks respectively.[2]]

I have identified a quantitative use for proton NMR spectroscopy.[1]

I have described the technique for the quantitative use of proton NMR spectroscopy.[2]

FROM LESSON 12B

Questions from multiple lessons

14. B. According to the spectroscopy information given, the compound must have two non-equivalent carbon environments, three non-equivalent proton environments, and a molar mass of 60 g mol^{-1}. Whilst each structure given would produce 2 peaks in their ^{13}C-NMR spectra, only the structures given in options B and C would produce 3 peaks in their ^{1}H-NMR spectra. Whilst the absorption peak at 3350 cm^{-1} could be caused by either the O–H (alcohol) group (3200–3600 cm^{-1}) shown in option B or the N–H (amine) group (3300–3500 cm^{-1}) shown in option C, only option B has a molar mass of 60 g mol^{-1}. Hence, only option B, 2-propanol, is consistent with the information given.

FROM LESSONS 10A, 10B & 10C

15. a. $M(\text{molecular ion}) = 60 \text{ g mol}^{-1}$

$M(CH_2O) = 30 \text{ g mol}^{-1}$

Given the molar mass of the molecular ion is double the molar mass of the empirical formula, doubling the empirical formula will give the appropriate molecular formula. (1 MARK)

$(CH_2O) \times 2 = C_2H_4O_2$ (1 MARK)

Alternative answer:

$M(\text{molecular ion}) = 60 \text{ g mol}^{-1}$

$M(C_nH_{2n}O_n) =$

$(n \times 12.0 \text{ g mol}^{-1}) + (2n \times 1.0 \text{ g mol}^{-1}) + (n \times 16.0 \text{ g mol}^{-1})$

$60 \text{ g mol}^{-1} = 30n \text{ g mol}^{-1}$

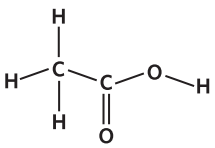
$n = \dfrac{60 \text{ g mol}^{-1}}{30 \text{ g mol}^{-1}}$

$n = 2$ (1 MARK)

Therefore, the molecular formula of the molecule is $C_2H_4O_2$. (1 MARK)

b. Aside from the TMS reference peak, there are 2 other distinct peaks on the spectrum. Hence, there are 2 different proton environments in the molecule.

c.



d. The broad peak at 2500–3300 (cm^{-1}) indicates the presence of an O–H (acid) bond.

e. Ethanoic acid

FROM LESSONS 7A, 7B, 10A & 10B

10E Chromatography

Progress questions

1. D. In chromatography, the components of a sample adsorb to and desorb from the stationary phase continuously.

2. A. With a polar stationary phase, the most polar sample is most strongly attracted to the stationary phase. The sample most attracted to the stationary phase moves the smallest distance from the origin. Hence, sample A is the most polar.

3. C. Increasing the temperature typically increases the solubility of substances, meaning the component will more readily dissolve in the mobile phase. Therefore, the component will pass through the column more quickly and have a lower retention time.

4. D. All conditions must be identical when comparing experimentally obtained retention times to known retention times.

5. D. Since each alcohol is a primary alcohol containing only one hydroxyl functional group, each compound contains a non-polar hydrocarbon chain with a polar O–H group on the end carbon. Hence, the alcohol with the longest retention time will be the alcohol with the longest non-polar hydrocarbon chain, and therefore the alcohol with the highest molar mass. Since alcohol 4 has the longest retention time, it must have the highest molar mass.

6. A. Butane (non-polar) molecules will be more strongly attracted to the non-polar mobile phase (hexane) than butanoic acid (polar) molecules. In all other options the mixture contains chemicals that are both polar or both non-polar, so the differences in attraction to the mobile phase and retention times will be less significant.

Deconstructed

7. C **8.** D

9. A. Vitamin C contains four polar hydroxyl functional groups in a relatively short carbon skeleton, making it the most polar. It is therefore expected to have the shortest retention time. Octane consists of one long non-polar carbon chain, making it the most non-polar. It is therefore expected to have the longest retention time. Heptanol contains a single hydroxyl group at the end of a long non-polar carbon chain, making it less polar than vitamin C but more polar than octane. It is therefore expected to have a retention time in between that of vitamin C and octane.

Exam-style

10. D. Polar molecules will be more attracted to the polar mobile phase by dipole-dipole attraction. Non-polar molecules will be more attracted to the non-polar stationary phase by dispersion forces. The polar molecules are more attracted to the polar solvent (mobile phase) and so will travel through the column faster than the non-polar molecules, which are more attracted to the non-polar stationary phase.

11. D. The most polar compound will dissolve most readily in the polar mobile phase, and will hence pass most quickly through the column, resulting in the shortest retention time. Looking at the structures of each amino acid, asparagine is the most polar, and will therefore have the shortest retention time. Whilst alanine and leucine are both relatively non-polar, leucine has a much larger non-polar side group, making it the least polar. Hence, leucine will pass through the column most slowly and will have the longest retention time.

12. a. $0.30\ g\ L^{-1}$

b. Diluted soft drink solution (100 mL containing 5.0 mL of soft drink) is diluted by a factor of 25 (10 mL into 250 mL) for testing in HPLC.

c(sucrose) in 100 mL solution made from soft drink $= 25 \times c$(sucrose) in tested sample

c(sucrose) in 100 mL solution made from soft drink $= 25 \times 0.30\ g\ L^{-1}$

c(sucrose) in 100 mL solution made from soft drink $= 7.5\ g\ L^{-1}$

c(sucrose) in 100 mL solution made from soft drink $= \frac{7.5\ g\ L^{-1}}{1000}$

c(sucrose) in 100 mL solution made from soft drink $= 0.0075\ g\ mL^{-1}$ (1 MARK)

m(sucrose) in 5.0 mL soft drink = m(sucrose) in 100 mL solution

m(sucrose) in 5.0 mL soft drink $= c \times V$

m(sucrose) in 5.0 mL soft drink $= 0.0075\ g\ mL^{-1} \times 100\ mL$

m(sucrose) in 5.0 mL soft drink $= 0.75\ g$ (1 MARK)

c(sucrose) in 5.0 mL soft drink $= \frac{m}{V}$

c(sucrose) in 5.0 mL soft drink $= \frac{0.75\ g}{5.0\ mL}$

c(sucrose) in 5.0 mL soft drink $= 0.15\ g\ mL^{-1}$ (1 MARK)

m(sucrose) in 330 mL soft drink $= c \times V$

m(sucrose) in 330 mL soft drink $= 0.15\ g\ mL^{-1} \times 330\ mL$

m(sucrose) in 330 mL soft drink $= 49.5\ g$

m(sucrose) in 330 mL soft drink $= 50\ g$ (2 sig. figs) (1 MARK)

c. The temperature of the column could have been decreased.

Alternative answers:

- The length of the column could have been increased.
- The total surface area of the stationary phase could have been increased.
- A more viscous mobile phase could have been used.

Key science skills

13. a. Rate of production of DKP

Alternative answers:

- Change in concentration of DKP over time
- Change in amount of DKP over time

b. [Calibrate the high-performance liquid chromatography (HPLC) under the same experimental conditions.[1]][Run a range of standard solutions for DKP.[2]][Use the HPLC results from these standards to produce a calibration curve.[3]]

✓ ✗	I have explained that the HPLC setup must be calibrated under the same experimental conditions.[1]
✓ ✗	I have explained that a range of standard solutions for DKP should be run through the HPLC setup.[2]
✓ ✗	I have explained that the standard solutions should be used to produce a calibration curve.[3]

c. Increasing the length of the column

Alternative answers:

- Altering the mobile or stationary phases
- Altering the temperature of the column

d. Increasing the length of the column, altering either the mobile or stationary phases, or altering the temperature of the column all lead to improved resolution of peaks, which in turn leads to a more reliable analysis of peak areas and subsequently the concentrations of aspartame and DKP.

e. As the temperature increases, the concentration of DKP shows a general increase.

Alternative answers:

- With the exception of the outlier at 25 °C, the trend indicates that as temperature increases, the concentration of DKP increases.
- There is no consistent trend in DKP as the 15 °C trial shows a decrease in DKP concentration compared to other temperatures, which show an average increase.

f. The initial concentration DKP/aspartame was not known (i.e. no analysis of either DKP or aspartame was done at time = 0).

g. The lack of initial concentration values means it cannot be assumed that the starting concentrations of aspartame and DKP were the same in each can. Therefore, the final concentrations cannot be relied upon as a measure of the production of DKP. Hence, the validity of the experiment is compromised.

FROM LESSONS 12A, 12B, 12C, 12D & 12E

Questions from multiple lessons

14. a. [Glycerol would be found in the aqueous layer[1]][as it is capable of forming hydrogen bonds with water due to its hydroxyl groups.[2]]

✓ ✗	I have identified that glycerol would be found in the aqueous layer.[1]
✓ ✗	I have explained how glycerol is soluble in water.[2]

Alternative answers:

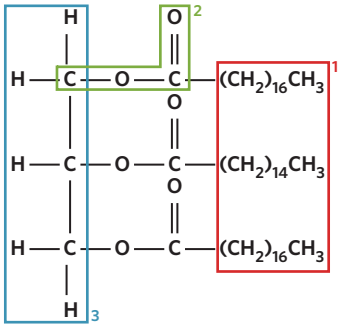
- Methanol would be found in the aqueous layer as it is capable of forming hydrogen bonds with water due to its hydroxyl groups.
- Potassium hydroxide/potassium ions/hydroxide ions would be found in the aqueous layer as they are soluble in water by ion-dipole bonding.

b. The peak areas suggest that there are approximately twice as many molecules of methyl ester B as there are of methyl ester A.

c. Name: Methyl stearate (1 MARK)

Semi-structural formula: $CH_3(CH_2)_{16}COOCH_3$ (1 MARK)

d.



✓ ✗ I have drawn the semi-structural formulas for one $(CH_2)_{14}$ and two $(CH_2)_{16}$ residues.[1]

✓ ✗ I have accurately drawn the ester group.[2]

✓ ✗ I have accurately drawn the glycerol backbone.[3]

e. i. From the mass-to-charge ratio of the molecular ion, $M(C_{17}H_{34}O_2) = 270.0\ g\ mol^{-1}$.

$$n(C_{17}H_{34}O_2) = \frac{m}{M}$$

$$n(C_{17}H_{34}O_2) = \frac{2.28\ g}{270.0\ g\ mol^{-1}}$$

$$n(C_{17}H_{34}O_2) = 8.444 \times 10^{-3}\ mol \quad (1\ MARK)$$

$$\text{Energy released} = CF \times \Delta T$$

$$\text{Energy released} = 42.4\ kJ\ °C^{-1} \times 1.18\ °C$$

$$\text{Energy released} = 50.03\ kJ \quad (1\ MARK)$$

$$\Delta H_{molar} = -\frac{q}{n(\text{fuel combusted})}$$

$$\Delta H_{molar} = -\frac{50.03\ kJ}{8.444 \times 10^{-3}\ mol}$$

$$\Delta H_{molar} = -5.92 \times 10^3\ kJ\ mol^{-1} \quad (1\ MARK)$$

ii. $C_{17}H_{34}O_2(l) + \frac{49}{2}O_2(g) \rightarrow 17CO_2(g) + 17H_2O(g)$ (1 MARK)
$\Delta H = -5.92 \times 10^3\ kJ\ mol^{-1}$ (1 MARK)

Alternative answer:

- $2C_{17}H_{34}O_2(l) + 49O_2(g) \rightarrow 34CO_2(g) + 34H_2O(g)$ (1 MARK)
  $\Delta H = -1.18 \times 10^4\ kJ$ (1 MARK)

FROM LESSONS 1D, 2B, 8A & 10A

10F Combining techniques

Progress questions

1. B. Infrared spectroscopy provides the most information about the types of functional groups present, whilst ^{13}C-NMR spectroscopy provides the most information about the number of carbon environments.

2. C. The absorption ranges and shapes of the peaks on an infrared spectrum can be compared to the characteristic absorption ranges and shapes of peaks caused by certain functional groups.

Deconstructed

3. D **4.** B

5. D. NMR spectroscopy provides the most information about the structure of the compound. The number of peaks in the ^{13}C and ^1H-NMR spectra indicate the number of carbon and proton environments, whilst the peak areas and splitting patterns on the ^1H-NMR spectrum can indicate the ratio of protons in each environment and the number of protons in each neighbouring environment. All isomers of C_4H_9Cl would show largely similar mass, and whilst the fingerprint regions could be used to identify the compound and hence its structure, this is not as useful as simply analysing the NMR spectra. The isomers of C_4H_9Cl also demonstrate similar polarity, and therefore similar retention times under the same conditions, so HPLC would not be particularly useful in identifying the compound.

Exam-style

6. a. The chromatogram shows a peak at a retention time of 2 minutes which aligns with pure aspirin, however there is an additional peak at 4 minutes which indicates the presence of an impurity.

b. [NMR spectroscopy[1]][could be used to identify the number of non-equivalent carbon and proton environments, as well as the number of protons in each environment and the number of neighbouring protons.[2]][Infrared spectroscopy[3]][could be used to identify the types of bonds and possible functional groups present in the compound.[4]]

✓ ✗ I have identified NMR spectroscopy as a possible analysis technique.[1]

✓ ✗ I have explained how NMR spectroscopy can be used in determining the structure and identity of the unknown compound.[2]

✓ ✗ I have identified infrared spectroscopy as a possible analysis technique.[3]

✓ ✗ I have explained how infrared spectroscopy can be used in determining the structure and identity of the unknown compound.[4]

7. a. C=O, 1750 cm^{-1} (1670–1750 cm^{-1}) or C–H, 3000 cm^{-1} (2850–3300 cm^{-1})

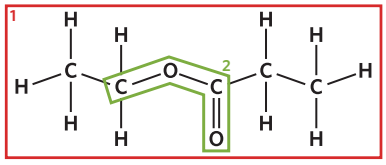
b. Four proton environments

c. The triplet splitting patterns at 1.1 ppm and 1.3 ppm indicate two instances of the presence of two H atoms on a neighbouring C atom.

Alternative answer:

- The quadruplet splitting patterns at 2.3 ppm and 4.1 ppm indicate two instances of the presence of 3 H atoms on a neighbouring C atom.

d.



✓ ✗ I have correctly drawn 2 ethyl groups connected by an ester linkage.[1]

✓ ✗ I have correctly drawn an ester linkage.[2]

e. The ^{13}C-NMR spectrum shows five peaks consistent with the five different carbon environments shown in the structure.

Key science skills

8. a.

Spectroscopic technique	Information provided
Mass spectrum	[The parent (molecular) ion peak at $m/z = 88$ [1]][is consistent with the molar (relative molecular) mass of ethyl ethanoate, $CH_3COOCH_2CH_3$.[2]]
Infrared spectrum	[Strong absorption around 1750 cm^{-1} is consistent with the presence of a C=O bond in a ketone (1680–1850 cm^{-1}) or ester (1720–1840 cm^{-1}).[3]][This is consistent with the C=O (ester) bond present in ethyl ethanoate, $CH_3COOCH_2CH_3$.[4]]
^{1}H-NMR spectrum	[The three different sets of peaks indicate that the compound has three different proton environments,[5]][which is consistent with the three different proton environments in ethyl ethanoate, $CH_3COOCH_2CH_3$.[6]]

✓ ✗ I have identified the parent (molecular) ion peak at $m/z = 88$.[1]

✓ ✗ I have explained how this is consistent with the molar mass of ethyl ethanoate.[2]

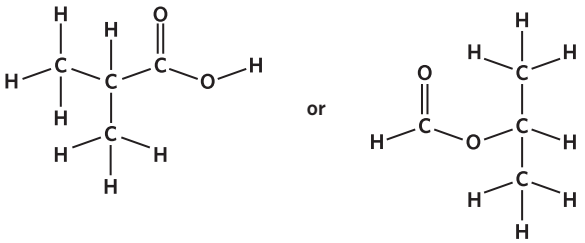
✓ ✗ I have identified the bond types consistent with a strong absorption band at 1750 cm^{-1}.[3]

✓ ✗ I have explained how this is consistent with the ester bond present in ethyl ethanoate.[4]

✓ ✗ I have identified the three distinct sets of peaks on the ^{1}H-NMR spectrum.[5]

✓ ✗ I have explained how this is consistent with the three different proton environments in ethyl ethanoate.[6]

b.



FROM LESSON 12C

Questions from multiple lessons

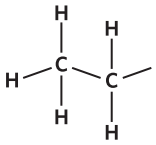
9. a. Double covalent bond between a carbon atom and oxygen atom in an acid, ketone, or ester (C=O)

b. Three carbon environments

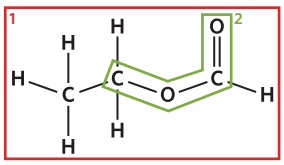
c. Three proton environments

d. i. According to the n + 1 rule, a triplet arises from two neighbouring equivalent protons.

ii.



e. Since compound X does not react with a base, it cannot be a carboxylic acid.



✓ ✗ I have drawn the structure of the ester ethyl methanoate.[1]

✓ ✗ I have correctly drawn the ester linkage.[2]

FROM LESSONS 7A, 8A, 10B, 10C & 10D

Chapter 10 review

Multiple choice

1. B. When infrared energy is absorbed, much of it is converted into kinetic energy, causing increased stretching and vibration of covalent bonds.

2. A. Mass spectroscopy can be used to determine the relative abundances of isotopes of elements.

3. B. The high resolution ^{1}H-NMR spectrum for 1,1,1-trichloropropane would show two peaks, one with a quartet splitting pattern and the other with a triplet splitting pattern. The high resolution ^{1}H-NMR spectrum for 1,2,3-trichloropropane would show two peaks, one with a quintet splitting pattern and the other with a doublet splitting pattern.

4. C. All positively charged ions will register as peaks on the mass spectrum.

5. A. The largest difference in retention times will produce the largest separation of the three substances.

6. C. Repetition of the exercise should reduce the impact of errors and the uncertainty, thereby making the results more precise.

7. D. A mixture of hydrocarbon molecules would be quite volatile, meaning the hydrocarbons would be readily available in the gas phase. The use of gas chromatography enables the separation of each individual hydrocarbon component, and the use of mass spectrometry allows for the identification of the individual components.

8. A. Since the compound reacts with acid, it must be either $CH_3CH_2CH_2COOH$ or $(CH_3)_2CHCOOH$. While both $[COOH]^+$ and $[CH_3CH_2O]^+$ are consistent with $m/z = 45$, only $[COOH]^+$ is consistent with the compound being an acid.

9. D. The peak at 3300 cm^{-1} could be due to the O—H of an alcohol or acid, or the N—H of an amide or amine. The peak at 1680 cm^{-1} could be due to the C=O bond of an amide, aldehyde, acid or ketone, or the C=C bond of an alkene. The only compound consistent with this information is octanamide, which contains an N—H (amide) bond and a C=O (amide) bond.

10. B. Chloromethane is the most polar molecule, meaning it is most readily dissolved in the polar mobile phase, and will therefore elute from the column most quickly, giving it the lowest retention time. Additionally, chloromethane has the smallest molar mass, also allowing it to elute from the column more quickly.

Short answer

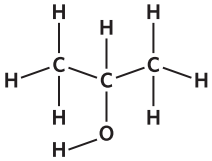
11. a. i. Two carbon environments

ii. Three hydrogen environments

iii. According to the n + 1 rule, a septet arises from six neighbouring protons combining into one peak.

b. Oxygen and hydrogen (O—H bond)

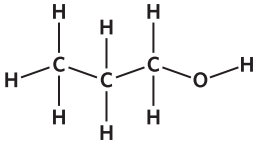
c.



12. a. V, U, T, S

b. The alcohol present in the highest concentration is the alcohol with the largest peak area, which is alcohol T.

c.



d. The bass peak corresponds to an ion with a mass-to-charge ratio of $m/z = 31$. Hence, a possible fragment ion with a charge of +1 must have a molar mass of 31 g mol^{-1}.

$M([CH_2OH]^+) = 12.0\ g\ mol^{-1} + (3 \times 1.0\ g\ mol^{-1}) + 16.0\ g\ mol^{-1}$

$M([CH_2OH]^+) = 31\ g\ mol^{-1}$

Hence, a possible fragment ion that could be responsible for the base peak is $[CH_2OH]^+$.

e. [Gas chromatography can be used to separate each alcohol from the mixture based on their relative molar masses.[1]] [Each alcohol can then be analysed individually using mass spectrometry to identify the mass-to-charge ratio of the parent molecular ions, and hence, the molar masses of each alcohol.[2]]

✓ ✗ I have explained how gas chromatography can be used to separate the alcohols in the mixture.[1]

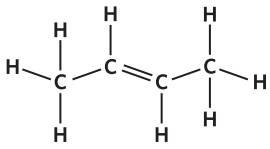
✓ ✗ I have explained how mass spectrometry can be used to identify the molar masses of the alcohols.[2]

13. a. i. $m/z = 41$

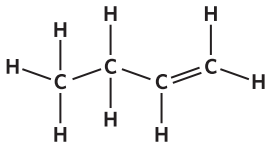
ii. C_4H_8

iii. $[C_3H_5]^+$

b.

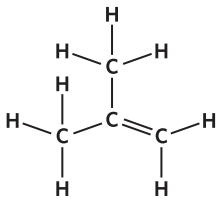
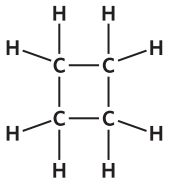


(1 MARK)



(1 MARK)

Alternative answers:

- 
- 

c. i. $CH_3CH_2CHCH_2$

ii. 1-bromobutane

d. [Hydration of 1-butene produces an alcohol, so the spectrum should show the broad absorption peak of the O—H of an alcohol at 3200–3600 cm^{-1}.[1]] [Additionally, the spectrum should show a peak at 2850–3090 cm^{-1} caused by the C—H bonds present in the compound.[2]] [Only spectrum Y is consistent with this information, showing both the O—H (alcohol) peak at 3400 cm^{-1} and the C—H (alkanes, alkenes, arenes) peak at 3000 cm^{-1}.[3]]

✓ ✗ I have identified that an O—H (alcohol) peak should appear on the spectrum at 3200–3600 cm^{-1}.[1]

✓ ✗ I have identified that a C—H (alkanes, alkenes, arenes) peak should appear on the spectrum at 2850–3090 cm^{-1}.[2]

✓ ✗ I have deduced which spectrum is consistent with the product of the hydration of Molecule L.[3]

14. a. [The peak at 3200 cm^{-1} corresponds to the O—H bond of an acid.[1]] [The peak at 1700 cm^{-1} corresponds to the C=O bond of an aldehyde, acid or ketone.[2]]

✓ ✗ I have identified the bond(s) corresponding to the peak at 3200 cm^{-1}.[1]

✓ ✗ I have identified the bond(s) corresponding to the peak at 1700 cm^{-1}.[2]

b. According to the mass spectrum, the form of the molecular ion containing ^{35}Cl has a mass-to-charge ratio of $m/z = 108$.

$M(C_xH_y) = 108 \text{ g mol}^{-1} - (2 \times 16.0 \text{ g mol}^{-1}) - 35 \text{ g mol}^{-1}$

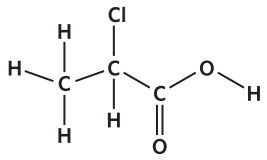
$M(C_xH_y) = 41 \text{ g mol}^{-1}$ (1 MARK)

The only possible combination of C and H atoms that sum to a relative molecular mass of 41 g mol^{-1} is C_3H_5. Hence, $x = 3$ and $y = 5$. (1 MARK)

c. i. There is a 1 : 1 : 3 ratio of protons in each non-equivalent proton environment.

ii. One proton environment has one neighbouring proton, another proton environment has three neighbouring protons, and the third proton environment has zero neighbouring protons.

iii.

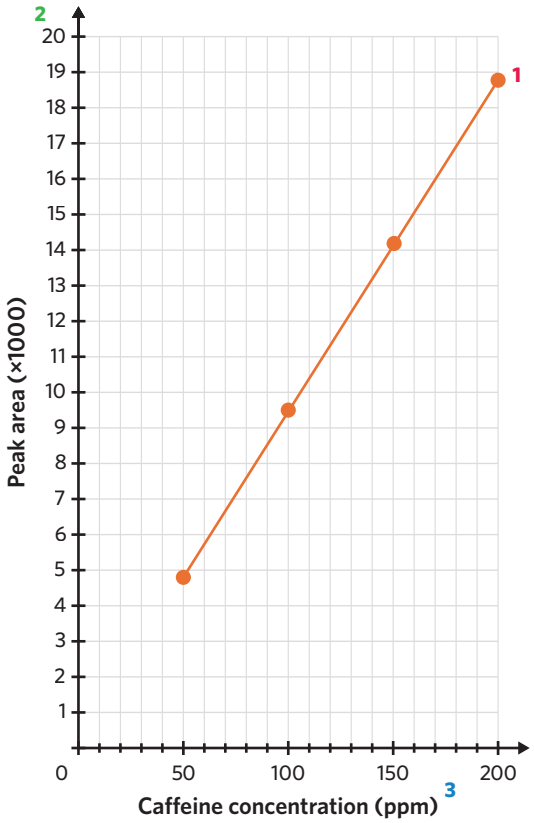


d. [The presence of the two chlorine isotopes ^{35}Cl and ^{37}Cl give rise to two molecular ion peaks,[1]][one corresponding to $[CH_3CH^{35}ClCOOH]^+$ and one corresponding to $[CH_3CH^{37}ClCOOH]^+$.[2]]

- I have identified the presence of two different chlorine isotopes.[1]
- I have given the semi-structural formulas for each compound.[2]

Key science skills

15. a.



- I have correctly plotted the points and drawn a suitable line of best fit.[1]
- I have used an appropriate scale for the graph.[2]
- I have labelled the axes of the graph appropriately.[3]

b. 127 ppm (accept range of answers within 125–130 ppm)

c. i. The absence of a peak at a retention time of 96 seconds suggests that the soft drink does not contain caffeine.

ii. The peak area of the caffeine peak (211 000) is well beyond the range of the calibration curve (~18 800). Extrapolating outside the range of the standard solutions does not give an accurate indication of the caffeine content of the espresso coffee sample.

iii. The espresso coffee sample can be diluted to bring its caffeine concentration within the range of the calibration curve.

FROM LESSONS 12B, 12C & 12E

16. [The methyl esters all contain the ester functional group so retention times will depend on molecular mass/size and extent of unsaturation.[1]][Pure samples of each of the methyl esters can be run through the HPLC instrument under identical conditions to determine the individual retention times of each methyl ester.[2]] [The relative amounts of each methyl ester, and hence percentage composition of the egg yolk, can be determined from the relative areas under the peaks/peak heights at the retention times of each methyl ester.[3]]

- I have explained how the methyl esters can be separated based on molecular size and extent of unsaturation.[1]
- I have explained that pure samples of each methyl ester should first be run through the HPLC instrument.[2]
- I have explained how the relative amounts of each methyl ester can be determined from the relative areas under the peaks.[3]

FROM LESSONS 12B & 12E

11A Extraction, purification and identification of medicinal molecules

Progress questions

1. B. Generally in solvent extraction, solvents with significant differences in polarity are used.

2. A. Distillation (using a heating mantle, for fuels) can be used to separate compounds with similar polarities yet significantly different boiling points.

3. D. Since oils have high boiling points, high temperatures are necessary for simple distillation, and these may cause decomposition of oils.

4. D. Medicinal molecules are often large, have polar groups, and contain rings.

5. C. The broad trough at 3200-3600 is indicative of an O—H (alcohol) bond, most likely in an —OH (hydroxyl) group.

6. B. Carbon atom B is attached to four unique environments (do not forget the hydrogen atom, which is not shown in skeletal structures), whereas carbon atoms A, C, and D are attached to three, two, and two unique environments respectively.

7. C. The molecule in option C contains a single chiral centre (the second carbon).

8. C. Single bonds can rotate and hence the two structures are 180° rotations of each other.

9. D. Optical isomers can bind differently to receptors, but always rotate a plane of polarised light in opposite directions (a physical property). It is not always possible to separate optical isomers of a compound.

Deconstructed

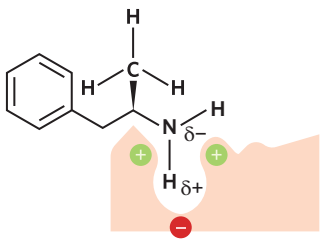
10. D

11. B

12. a. [Since dextroamphetamine is chiral, its mirror image is non-superimposable.[1]][As a result, this mirror image (optical isomer) is less likely to bind to the receptor, and will hence likely be less effective as a medicine.[2]]

- ✓ ✗ I have explained that dextroamphetamine has an optical isomer.[1]
- ✓ ✗ I have explained that this optical isomer would be less likely to bind to this receptor.[2]

b.



Exam-style

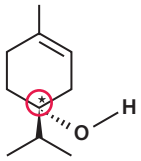
13. a. i. [Solvent extraction could be used to separate (largely non-polar) tea tree oil from polar impurities,[1]][and steam distillation could be used to further purify it with minimal decomposition of the oil.[2]]

- ✓ ✗ I have identified that solvent extraction could remove polar impurities.[1]
- ✓ ✗ I have identified that steam distillation could purify tea tree oil.[2]

ii. HPLC could be used to qualitatively and quantitatively determine the compounds in tea tree oil.

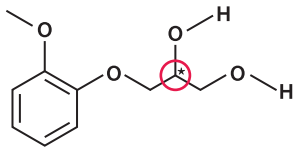
iii. MS, ^{13}C-NMR, ^{1}H-NMR, and IR could be used to determine the structures and functional groups of the compounds in tea tree oil.

b. i.

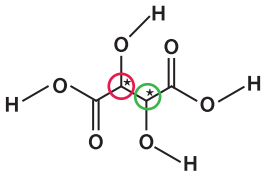


ii. For chiral medicinal molecules, one optical isomer may bind differently to receptors in the body compared with the other optical isomer, leading to potentially differing effectiveness and safety between optical isomers.

14. a. i.



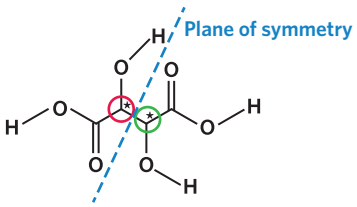
ii.



b. i. [Guaifenesin is chiral,[1]][since it contains exactly one chiral centre or since it has a non-superimposable mirror image.[2]]

- ✓ ✗ I have identified guaifenesin as chiral.[1]
- ✓ ✗ I have explained why guaifenesin is chiral.[2]

ii. [Tartaric acid is achiral,[1]][since although it contains two chiral centres, it also has a plane of symmetry / since its mirror image is superimposable.[2]]



- ✓ ✗ I have identified tartaric acid as achiral.[1]
- ✓ ✗ I have explained why tartaric acid is achiral.[2]

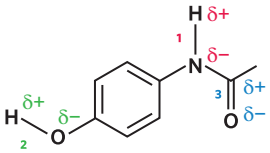
15. a. [Salicin is predominantly polar, whereas flavone is mostly non-polar.[1]][As a result, both water and a less polar solvent such as acetone (propanone) or hexane could be placed in a separating funnel to undertake solvent extraction.[2]][Salicin would largely dissolve in the water, whereas flavone would largely dissolve in the less polar solvent, allowing separation.[3]]

- I have identified the polarity of the two compounds.[1]
- I have identified a suitable pair of solvents for solvent extraction.[2]
- I have explained how these solvents would allow separation of the two compounds.[3]

b. [A temperature towards the middle of the range 367–549 °C would be appropriate for distillation,[1]][as at this temperature, salicin is a liquid whereas flavone is a gas, allowing separation of the two compounds.[2]]

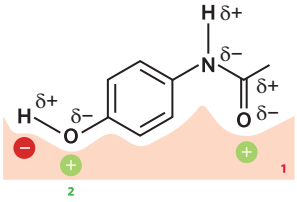
- I have identified a suitable temperature for distillation.[1]
- I have explained why this temperature is suitable.[2]

16. a.

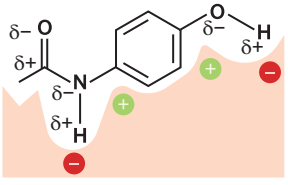


- I have identified the partial charges of the amino group.[1]
- I have identified the partial charges of the hydroxyl group.[2]
- I have identified the partial charges of the carbonyl group.[3]

b.



or



- I have drawn a possible shape for the receptor.[1]
- I have drawn the possible charges of sites on the receptor.[2]

c. [Paracetamol is achiral,[1]][since each of its atoms is attached to a maximum of three unique environments, and hence paracetamol has no chiral centre.[2]]

- I have identified paracetamol as achiral.[1]
- I have explained why paracetamol is achiral.[2]

d. Since paracetamol is achiral, its mirror image is superimposable and is hence not likely to bind differently to receptors in the body.

Key science skills

17. a. i. Picking leaves from a eucalyptus tree could harm the tree.

Alternative answers:

- Collect already-fallen leaves if possible.
- Pick as few leaves as possible from the tree, minimising waste.

ii. Steam distillation requires high temperatures and can be energy-intensive.

Alternative answers:

- Ensure the distillation apparatus is well-insulated.
- Use renewable energy to heat the substances.

b. [Dry and grind the collected eucalyptus leaves to a powder, then dissolve them in an appropriate solvent.[1]][Place this solution in a distilling flask and feed water into the distillation apparatus to be vaporized.[2]][Heat the solution until eucalyptol evaporates, allowing it to recondense separately and be collected.[3]]

- I have given a method step for the conversion of eucalyptus leaves to a distillable form.[1]
- I have given a method step for the setup of the steam distillation apparatus.[2]
- I have given a method step for separation and collection of eucalyptol.[3]

FROM LESSONS 12B & 12E

Questions from multiple lessons

18. a. [Citral: 3,7-dimethylocta-2,6-dienal.[1]]
[Citronellal: 3,7-dimethyloct-6-enal.[2]]

- I have given the correct systematic name of citral.[1]
- I have given the correct systematic name of citronellal.[2]

b. [As both compounds are very similar in structure and size, they likely have similar boiling points.[1]][Moreover, since they each contain one polar aldehyde group and a large, non-polar hydrocarbon chain, they also have very similar polarities.[2]]
[These factors combine to make it very difficult to separate these compounds using solvent extraction or steam distillation.[3]]

- I have identified the two compounds as having similar boiling points.[1]
- I have identified the two compounds as having similar polarities.[2]
- I have evaluated the difficulty of separating the two compounds.[3]

c. [Myrcene is entirely non-polar, whereas citral and citronellal are slightly polar.[1]][As a result, solvent extraction using a non-polar solvent (e.g. hexane) and a somewhat polar solvent (e.g. ethanol) could potentially be used to separate myrcene from citral and citronellal.[2]]

✓ ✗ I have identified the difference in polarities of myrcene and citral/citronellal.[1]

✓ ✗ I have explained how solvent extraction could exploit this difference in polarities.[2]

FROM LESSON 7B

19. a. [Coumarin is also present in the vanilla essence sample.[1]] [This can be ascertained because there is a peak on the HPLC chromatogram for vanilla essence at retention time = 18 minutes, which is the retention time of coumarin determined under identical conditions.[2]]

✓ ✗ I have identified that coumarin is present in the vanilla essence sample.[1]

✓ ✗ I have explained how HPLC can be used for qualitative analysis.[2]

b. [The IR spectrum for vanillin shows a broad trough at approximately 3500 cm^{-1}.[1]][This indicates the presence of an O–H bond in an alcohol, corresponding with an hydroxyl group.[2]][The IR spectrum for vanillin also shows a narrow yet significant trough at approximately 1660 cm^{-1}.[3]] [This indicates the presence of a C=O bond, likely corresponding with a carbonyl group in an aldehyde.[4]]

✓ ✗ I have identified the broad trough at 3500 cm^{-1}.[1]

✓ ✗ I have identified the presence of an hydroxyl group.[2]

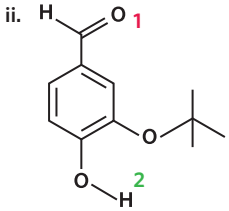
✓ ✗ I have identified the narrow trough at 1660 cm^{-1}.[3]

✓ ✗ I have identified the presence of a carbonyl group.[4]

c. 152 $g\ mol^{-1}$

d. i. $C_8H_8O_3$

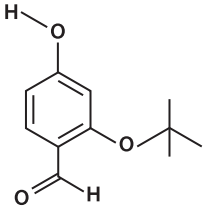
ii.



✓ ✗ I have correctly drawn –CHO attached to the ring.[1]

✓ ✗ I have correctly drawn –OH attached to the ring.[2]

Alternative answer:



FROM LESSON 10F

11B Enzymes and medicines

Progress questions

1. B. Amino acids all have an amino group and a carboxyl group positioned on the second carbon and are called 2-amino acids or α-amino acids.

2. D. All of the forces (along with hydrogen bonding) maintain the tertiary structure of a protein.

3. D. Hydrogen bonds are found in the secondary, tertiary, and quaternary structures.

4. B. The shapes of most enzymes are specific to particular substrates.

5. A. The covalent bonds in the primary structure of an enzyme will not be broken at temperatures as low as 75 °C.

6. D. Most enzymes are very specific to a particular substrate.

7. C. Enzymes can be reused as they are not broken down or used up when they catalyse a reaction.

8. C. Zwitterions have a COO^- and an NH_3^+ group but no overall net charge.

9. C. They block unwanted reactions that can threaten the health of a human.

Deconstructed

10. B **11.** C

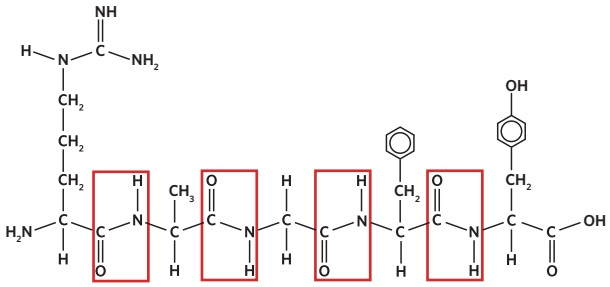
12. D. The primary, secondary and tertiary structures are accurately described in statements I, II, and III respectively.

Exam-style

13. C. Disulfide bridges are responsible for maintaining both the tertiary and quaternary structures.

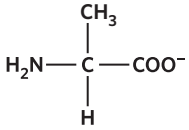
14. B. The enzyme is in excess and thus will not affect the rate if the concentration is increased further.

15. C. The amide linkage –CONH– joins the chain together.



16. D. If the enzyme activity were irreversible, the body would not have enough cholesterol (very important in making hormones and vitamin D) to maintain proper function.

17. a.



11B ANSWERS

b. [Hydrogen bonds.[1]][They form between the N and H & the O and H on different peptide bonds within the same polypeptide chain.[2]]

✓ ✗ I have identified the bonds.[1]

✓ ✗ I have explained how these are formed.[2]

18. [Primary structure: amide/peptide/covalent bonds.[1]] [Secondary structure: hydrogen bonds.[2]][Tertiary structure: hydrogen bonds, ionic interactions, disulfide bridges, permanent dipole-dipole forces, and dispersion forces.[3]] [Quaternary structure: hydrogen bonds, ionic interactions, disulfide bridges, dipole-dipole, and dispersion forces.[4]]

✓ ✗ I have determined the bonds present in the primary structure.[1]

✓ ✗ I have determined the bonds present in the secondary structure.[2]

✓ ✗ I have determined the bonds and forces of attraction present in the tertiary structure.[3]

✓ ✗ I have determined the bonds and forces of attraction present in the quaternary structure.[4]

Key science skills

19. a. [Since enzymes only operate in a narrow pH range, test tubes 1 & 3 with a pH of 1 and 14 respectively would result in lipase being denatured, meaning it would not function.[1]][As a result, Boglárka should still observe the cube of fat in test tubes 1 and 3, but in test tube 2 it should be broken down. [2]]

✓ ✗ I have stated the effect of pH on enzyme activity.[1]

✓ ✗ I have stated what Boglárka should observe.[2]

b. [A control has not been carried out, and the pH of the solution around the cube of fat could be affecting the results.[1]] [This could be remedied by setting up another 3 test tubes without the enzyme lipase, of pH 1.0, 4.5, and 14.0 respectively, to see if the pH itself has any effect on the size of the cube of fat.[2]]

✓ ✗ I have stated whether a control was carried out.[1]

✓ ✗ I have explained how the experiment could be improved in light of this.[2]

c. [The enzyme α-amylase's optimum pH range is very close to the pH of the mouth.[1]][Since an enzyme functions in a narrow pH range and the pH throughout the digestive tract varies, α-amylase can only function in the mouth.[2]]

✓ ✗ I have identified the optimum pH range of α-amylase.[1]

✓ ✗ I have explained why α–amylase can only function in the mouth.[2]

d. Denaturation affects the secondary, tertiary, and quaternary structures of an enzyme. It does not affect its primary structure.

FROM LESSON 12D

Questions from multiple lessons

20. a. The amino acid present in the sample was glutamic acid as it has an m/z of 147, whereas glycine has an m/z of 75.

b. [Glutamic acid has the greatest retention time.[1]][Due to the presence of an extra carboxyl group, glutamic acid is more polar than glycine. Therefore, it is more strongly adsorbed to the polar stationary phase and would in turn have the greater retention time.[2]]

✓ ✗ I have determined the amino acid with the greatest retention time.[1]

✓ ✗ I have compared the structure of both amino acids and the interaction with the stationary phase.[2]

FROM LESSONS 10A & 10E

21. a. I and III

b. i. [II. 'All catalysts are solid.'[1]][Catalysts can be solids, liquids, gases or aqueous solutions; for example, sulfuric acid/enzymes/H_3PO_4, etc.[2]]

✓ ✗ I have identified an incorrect statement.[1]

✓ ✗ I have explained why it is incorrect.[2]

ii. [IV. 'A catalyst lowers the enthalpy change of a reaction, enabling more particles to have sufficient energy to successfully react.'[1]][A catalyst does not change the relative energy contents of reactants and products. It does, however, lower the activation energy/increases the proportion of successful collisions/provides an alternative reaction pathway with the same overall ΔH.[2]]

✓ ✗ I have identified an incorrect statement.[1]

✓ ✗ I have explained why it is incorrect.[2]

iii. [V. 'A catalyst increases the value of the equilibrium constant, thus favouring the extent of the forward reaction, resulting in a greater yield of product.'[1]][A catalyst increases the rate of the forward and reverse reactions equally and does not affect the extent of a reaction, only temperature changes affect the value of k.[2]]

✓ ✗ I have identified an incorrect statement.[1]

✓ ✗ I have explained why it is incorrect.[2]

Alternative answers:

- VI. 'All catalysts align the reactant particles in an orientation that is favourable for a reaction to occur.' Enzymes/solid catalysts align (arrange) reactant particles into orientations that favour a reaction. However, liquid catalysts and gaseous catalysts do not arrange reactants in this way.
- VII. 'The effectiveness of a metal catalyst is not dependent upon its surface area.' Reaction occurs on the catalyst's surface. The larger the surface, the more 'effective' the catalysts.

- VIII. 'Enzymes are biological catalysts that catalyse a specific biochemical reaction once only'. Enzymes continue to catalyse specific chemical reactions because they are not consumed in the reactions or the tertiary structure/active site is not changed as a result of the reaction.
- IX. 'The effectiveness of an enzyme is independent of temperature'. Enzyme effectiveness depends on the shape of the active site/enzymes have an optimum operating temperature. At high temperatures the active site is denatured (changes shape).

FROM LESSONS 4A, 4B & 5B

Chapter 11 review

Multiple choice

1. B. Competitive inhibitors (a type of medicine) act by blocking an enzyme's usual activity, rather than enhancing it; Paclitaxel is a medicine extracted from plants that is approved for use in Australia; repeating the distillation process generally increases the purity of medicines.

2. A. Denaturation, which may be caused by high temperatures, is the irreversible disruption of some forces and bonds in the protein's secondary, tertiary, and quaternary structures.

3. A. Amide bonds exist between amino acids within polypeptide chains, whereas disulfide bonds occur between non-adjacent cysteine amino acids.

4. C. The tertiary structure involves the interactions and bonds between side chains within a protein, including disulfide bonds, which are the target of this new medicine.

5. A. In solutions of neutral pH, amino acids form zwitterions, which contain $-NH_3^+$ and $-COO^-$.

6. D. Amino acids may donate or accept a proton, and they are hence amphiprotic. In basic solutions (of high pH), the α-carbon exists in the $-COO^-$ form. The amino acids methionine and cysteine contain the element S.

7. C. Very high temperatures and acidity can disrupt the primary structure of proteins.

8. C. Carbon atom C is attached to four unique environments: $-OH$, $-CONCH_2CH_2CH_2OH$, $-H$, and $-C(CH_3)_2CH_2OH$. Carbon atoms A, B, and C are all attached to only three unique environments.

9. C. Due to their different 3D shape, optical isomers can bind differently to substances in the body, leading to unpredictable biological effects.

10. D. Salicin and verbenone have similar boiling points, yet very different solubilities in both water and hexane.

Short answer

11. a. i. Infrared (IR) spectroscopy analysis of the compound

ii. A combination of IR, MS, ^{1}H–NMR, and ^{13}C–NMR analysis of the compound

b. Polar groups enable atenolol to dissolve in aqueous solution, and hence enter the bloodstream and reach the heart.

c. [Atenolol acts as the 'key' in the 'lock', which represents a receptor in the heart.[1]][According to this model, atenolol is of the exact three-dimensional shape to fit the receptor and hence block it.[2]]

✓ ✗ I have identified the 'lock' and the 'key' in this situation.[1]

✓ ✗ I have explained that atenolol's 3D shape must fit the receptor.[2]

12. a. [A protein's secondary structure is determined by hydrogen bonding between $-C{=}O$ and $-N-H$ of the amide linkages in different sections of the protein's amino acid sequence.[1]] [This results in the formation of either α-helices or β-pleated sheets.[2]][A protein's tertiary structure is determined by the interactions between each amino acid residue's side chain.[3]] [These intermolecular forces include hydrogen bonding, ionic interactions, dispersion forces, disulfide bridges, and dipole-dipole forces.[4]]

✓ ✗ I have identified the origin of a protein's secondary structure.[1]

✓ ✗ I have described the structures that result from this hydrogen bonding.[2]

✓ ✗ I have identified the origin of a protein's tertiary structure.[3]

✓ ✗ I have specified the types of intermolecular forces present in a protein's tertiary structure.[4]

b. [The presence of a highly acidic solution (H^+) causes dramatic changes to any ionic interactions between charged amino acid side chains, and this permanently alters the interactions in the protein's tertiary structure.[1]][The protein is denatured as a result,[2]][with long protein chains folding over each other forming the 'clumps' in the solution.[3]]

✓ ✗ I have identified the effect of pH on a protein's tertiary structure.[1]

✓ ✗ I have linked this idea to the process of denaturation.[2]

✓ ✗ I have related this theory to the observed outcome in the experiment.[3]

13. [Enzymes are specific to a certain optical isomer,[1]][because the particular three-dimensional shape of the enzyme's active site only matches one three-dimensional optical isomer.[2]][Since the enzyme can break down only one of these optical isomers, half of the medicine will not be broken down in the body.[3]]

✓ ✗ I have identified enzymes as specific to a certain optical isomer.[1]

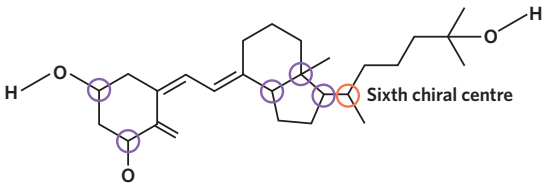
✓ ✗ I have explained why enzymes are specific to a certain optical isomer.[2]

✓ ✗ I have justified why this will result in the chemist's findings.[3]

14. [With elevated body temperatures, enzyme activity decreases, as more and more enzymes are denatured after exceeding their optimal temperatures.[1]][With lower body temperatures (below the optimal temperature), enzyme activity also decreases due to the lower kinetic energy.[2]][A decrease in enzyme activity is life-threatening because reactions that are necessary to sustain life proceed at a much slower rate.[3]]

- I have described the effect of higher temperatures on enzyme activity.[1]
- I have identified the effect of lower temperatures on enzyme activity.[2]
- I have explained how decreased enzyme activity affects human function.[3]

15. a.



b. [Although the active form of vitamin D contains multiple chiral centres, it has no plane of symmetry.[1]][As a result, its mirror image is non-superimposable, and the molecule is chiral.[2]]

- I have identified that the molecule has chiral centres but no plane of symmetry.[1]
- I have explained that the molecule's mirror image is non-superimposable.[2]

c. [Enzymes have active sites that are specific to one particular substrate molecule.[1]][The 24-hydroxylase enzyme will not be able to bind to another optical isomer of vitamin D due to its different orientation in space, which makes it non-superimposable and thus preventing it from acting as a substrate.[2]]

- I have described the specificity of an enzyme's active site.[1]
- I have linked this specificity to the concept of optical isomerism.[2]

d. [An enzyme lowers the activation energy of a reaction by providing an alternate reaction pathway.[1]][This means that a larger proportion of reactant molecules possess sufficient energy to react,[2]][leading to a higher proportion of successful collisions, which increases the overall rate of reaction.[3]]

- I have identified the effect of an enzyme on the activation energy of the reaction.[1]
- I have explained how this affects the energy threshold of the reactant molecules.[2]
- I have explained how this causes the overall change in reaction rate.[3]

e. [The lock-and-key model suggests that the enzyme has a very specific, rigid active site that binds with the substrate.[1]][Under this model, the substrate (vitamin D) binds to 24-hydroxylase's active site, catalysing vitamin D's breakdown without 24-hydroxylase changing shape.[2]]

- I have described the key principles of the lock and key model.[1]
- I have linked these principles to the reaction in the question.[2]

16. [Cooking the meat will minimise the risk of food poisoning by *E. coli*,[1]][as the high temperatures will denature the proteins in the bacteria, inhibiting their biological activity when ingested by the body.[2]]

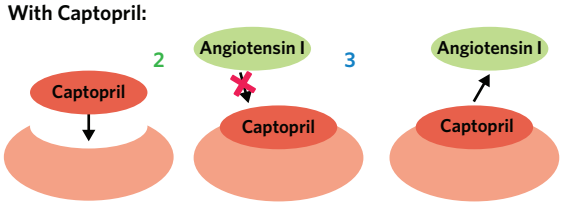
- I have identified a method of preventing food poisoning from *E. coli*.[1]
- I have explained how this method prevents food poisoning.[2]

Key science skills

17. a. Normal enzyme action:



With Captopril:



- I have a drawn the enzyme's usual action according to the lock-and-key model.[1]
- I have drawn captopril fitting the same 'lock' as angiotensin I.[2]
- I have drawn captopril preventing angiotensin I from converting to angiotensin II.[3]

b. [This is not a valid study,[1]][because using only company employees in the trial will likely introduce bias to the results.[2]]

- I have evaluated the study as invalid.[1]
- I have explained that the presence of bias invalidates the study.[2]

FROM LESSONS 12D & 12E

18. a. [For chiral medicines, often only one optical isomer binds to the desired receptor, whereas the other optical isomer could bind to another receptor (with potentially dangerous consequences).[1]][Since chiral medicines are often produced as a racemate which may not be easily separable, it can be difficult to ensure that only one optical isomer is present in the medicine, and hence ensure its safety and effectiveness.[2]]

✓ ✗ I have identified that optical isomers bind differently to receptors in the body.[1]

✓ ✗ I have explained why optical isomers are often difficult to separate from a racemate.[2]

b. i. The medicine's potential side effects and harms to various groups in society (for example, pregnant people) must be thoroughly researched.

ii. Laws surrounding the distribution and prescription of the medicine must be developed prior to approval.

Alternative answer:

- Research must be conducted to ensure that the medicinal molecule cannot be used to synthesise illegal substances.

iii. Research companies must have sufficient funding to thoroughly trial the safety and effectiveness of potential medicines.

FROM LESSON 12B

12A Scientific research

Progress questions

1. C. The purpose of scientific ideas is to gain knowledge.
2. B. Art interpretations are not based on objective evidence.
3. B. Scientific knowledge often contradicts previous studies – this is a major part of the 'knowledge–building' process. Science is not always correct at the first attempt, so when findings differ, analysis should be undergone into what may have caused these differences.
4. B. The basic scientific method begins with a brief introduction (including aim and hypothesis), followed by method, results, discussion, and conclusion.
5. D. Primary sources are those written by the original researcher(s).
6. D. An author's history and expertise are often important in determining the value of an article.
7. D. A hypothesis highlights the potential effect of the independent variable on the dependent variable.
8. C. The independent variable is the only variable that is deliberately changed in an experiment. There should only be one independent variable.

Deconstructed

9. B **10.** D
11. [The dependent variable is the degree of breakdown of the egg shell.[1]][The independent variable is the type of liquid in which the egg shell was placed.[2]]

✓ ✗ I have identified the dependent variable.[1]

✓ ✗ I have identified the independent variable.[2]

Exam-style

12. D. The independent variable is deliberately manipulated by the experimenter.
13. [The idea that Zodiac signs can influence current or future events has not been established using a scientific method.[1]][Therefore, the ideas are currently considered to be non-scientific.[2]]

✓ ✗ I have identified the need for a scientific method to classify an idea as scientific or not.[1]

✓ ✗ I have linked my answer to the question.[2]

14. **a.** The wavelengths/colours used in the experiment

b. [If the attraction of bugs to light depends on the wavelength of light used,[1]][then the colour that attracts the most bugs will reflect the wavelength that bugs are most attracted to.[2]]

✓ ✗ I have identified the effect of the independent variable on the dependent variable.[1]

✓ ✗ I have identified a possible outcome based on the relationship between the independent and dependent variable.[2]

15. C. More variables are controlled in option C (uses the same cell). In option D, a different cell is used, introducing variability.

12B Conducting an experiment

Progress questions

1. A. Qualitative analysis is useful for non-numeric data.
2. A. Litmus paper undergoes a colour change.
3. B. Primary data is collected directly by the experimenter.
4. D. Secondary data can be observational or numerical.
5. C. Science is an iterative and shared endeavour.
6. B. Considerations relating to staff and payment are economic in nature.
7. B. Scientific findings should be reported, regardless of whether they align with expectation or agenda.

Deconstructed

8. D **9.** B
10. [Although CO_2 increases can be seen in the increase in the rate of crop growth, the idea that an increased concentration of CO_2 can result in a decrease in the amount of nutrients present in the crop can have a negative economic impact.[1]][To get the same amount of nutrients, humans would need to eat more crops.[2]][This would likely require consumers to buy more food, thus raising costs of living and limiting food accessibility.[3]]

✓ ✗ I have identified the key idea from the passage.[1]

✓ ✗ I have identified the effect of the idea on nutrient consumption.[2]

✓ ✗ I have described the socio-economic impact of this idea.[3]

Exam-style

11. A. A water bath, rather than a Bunsen burner, should be used to minimise risk of ignition. The process should be carried out in a fume cupboard to minimise inhalation of organic vapours.
12. **a.** Secondary data

b. Plagiarism

13. **a.** Qualitative

b. [In his experiment, Luis is collecting data based on the different colour changes.[1]][This is classified as qualitative data.[2]][In order to calculate the amount of a substance present, Luis would need to collect quantitative data that gives numerical amounts.[3]][Unless Luis uses an analysis technique that allows the colours and their intensities to be translated into numerical values, Luis won't be able to calculate the amount of substance present by only using the data he collected.[4]]

✓ ✗ I have identified the data collected from the experiment.[1]

✓ ✗ I have identified the type of data collected from the experiment.[2]

- I have described the type of data that needs to be collected to calculate the amount of substance present.[3]
- I have identified what is required for Luis to calculate the amount of substance present.[4]

14. [The student should review the Safety Data Sheets (SDS) for each chemical,[1]][and ensure to follow all stipulated storage, handling and/or PPE guidelines.[2]]

- I have identified what the student should reference prior to undertaking the experiment.[1]
- I have identified the action the student should take.[2]

15. a. Ethical

b. [As vaccines are generally produced for human use, testing on humans would allow for the development of an effective vaccine in a shorter period of time.[1]][As a result, the vaccine would be available to affected individuals in a shorter period of time.[2]]

- I have identified the influence of human testing on rate of vaccine development.[1]
- I have described the impact of rate of vaccine development on human health.[2]

c. [Although human experimentation allows us to develop vaccines quickly using fewer resources, there is a chance that the individuals that are involved in the testing can become sick themselves.[1]][The alternative testing method that does not involve humans takes a significant amount of time, which could not only have high economic costs, but also means that those affected by disease may not be able to receive the appropriate treatment in time.[2]][When choosing a method, it is important that we consider and understand all of the immediate and secondary implications of the method.[3]]

- I have identified a disadvantage of human testing.[1]
- I have described the disadvantages of alternative methods.[2]
- I have identified the considerations when choosing an appropriate method.[3]

16. a. [Lab coat to avoid contact on the skin.[1]][Safety goggles to avoid contact with eyes.[2]]

- I have identified one item of PPE.[1]
- I have identified a second item of PPE.[2]

b. [Different experiments use different reagents, which carry their own risks.[1]][As a result, experimenters are required to develop a risk assessment specific to their experiment.[2]][Therefore, it is the experimenter and not the lab technician that should be writing the risk assessment.[3]]

- I have identified the nature of experimental risk.[1]
- I have identified the role of the experimenter in the risk management of an experiment.[2]
- I have linked my answer to the question.[3]

17. a. $H_2(g)$ is flammable and explosive.

Alternative answers:

- $Cl_2(g)$ is toxic.
- NaOH(aq) is corrosive.

b. Ensure there are no ignition sources present.

Alternative answers:

- Conduct experiment in fume hood.
- Limit contact with the solution and wear appropriate personal protective equipment.

18. a. The brand of bottled water

b. [The volume or temperature of the water used.[1]][The type of technique used for analysis.[2]][The types of reagents used or the amounts of reagent used.[3]]

- I have identified a variable.[1]
- I have identified a second variable.[2]
- I have identified a third variable.[3]

19. a. [If the level of sugar in drinks increases then the tax on manufacturers will increase.[1]][To avoid costs, there will be a decrease in the proportion of drinks with over 5 g sugar per 100 mL.[2]]

- I have referred to the independent variable in the hypothesis.[1]
- I have described the effect of the independent variable on the dependent variable.[2]

b. External ethical concern

c. [As mentioned in the passage, sugar can have negative health implications such as obesity and type 2 diabetes.[1]][The SDIL can create an incentive for companies to reduce the amount of sugar in their drinks.[2]][This means that there would be more drink options with less sugar available for people to consume.[3]][Therefore, the number of people with sugar-related disease would decrease.[4]]

- I have identified an impact.[1]
- I have described the effect of SDIL on the amount of sugar in drinks.[2]
- I have explained the effect of the SDIL on the availability of drinks with less sugar.[3]
- I have identified the overall impact on population health.[4]

12C Interpreting data

Progress questions

1. D. Experimental data can be represented in many different ways.
2. A. Qualitative and quantitative data are better represented in different ways.
3. A. Without values, pie charts show relative comparisons (proportions).
4. D. The purpose of scientific research is to identify the effect of the independent variable on the dependent variable.
5. C. For the graph, the x-axis represents the independent variable.
6. B. The dependent variable (irradiance) is affected by the independent variable (wavelength).
7. C. This is a view or judgement formed about something, not necessarily based on fact or knowledge.
8. A. Control groups are generally not subjected to the independent variable.
9. B. Not all relationships seen in experiments are causal.
10. C. Other variables can impact the experiment, and so also impact the conclusion drawn.
11. A. The supporting or refuting of a hypothesis depends on the results obtained in the experiment.

Deconstructed

12. C
13. A
14. [At the beginning of the experiment, the pH of the solution is close to 0.[1]][Therefore the original solution can be considered acidic, as acids have a pH lower than 7.[2]]

- ✓ ✗ I have used the graph to determine the pH of the original solution.[1]
- ✓ ✗ I have explained why the solution would be considered as acidic.[2]

Exam-style

15. a. As the reaction proceeds, the mass of the beaker and its contents remain the same.

    b. [According to the law of conservation of mass, no mass is lost or gained in a chemical reaction.[1]][Therefore, for the reaction in the experiment, which occurs in a sealed beaker, there would be no loss or gain in mass recorded as the reaction proceeds.[2]][This can be shown by the data presented in the graph, where there was no change in mass over time.[3]]

- ✓ ✗ I have identified the underlying chemical concept.[1]
- ✓ ✗ I have described the effect of the chemical concept.[2]
- ✓ ✗ I have used the data to justify my response.[3]

16. a. According to the graph, the world derives most of its electrical energy from fossil fuels, followed by hydro, nuclear, wind, other renewable resources then solar.

    b. [The use of fossil fuels both disrupts the earth (due to drilling) and produces greenhouse gases such as carbon dioxide, as well as dangerous compounds such as sulfur dioxide and nitric oxides.[1]][Due to the growing population, it is expected that more fuels will need to be consumed to increase the supply of energy.[2]][This could result in negative environmental impacts, which may cause a shift towards more environmentally conscious fuel alternatives.[3]]

- ✓ ✗ I have identified the main factors involved in the use of fossil fuels.[1]
- ✓ ✗ I have described the impact of a growing population on energy consumption.[2]
- ✓ ✗ I have identified a major impact of the use of energy resources over time.[3]

17. a. This allows the data to be plotted to a larger, more visible scale. If there were no breaks in the axes the plotted line would have to be very small.

    b. The density of water decreases with increasing temperature.

18. a. Quantitative data

    b. Different energy drinks contain different levels of caffeine.

    c. [There are major health concerns related to the consumption of energy drinks with high caffeine content.[1]][Therefore, it is inappropriate to have these drinks readily available for and tested on teenagers.[2]]

- ✓ ✗ I have identified the negative effects related to energy drinks.[1]
- ✓ ✗ I have identified an ethical consideration.[2]

    d. The control group would involve the consumption of non-caffeinated energy drinks.

19. a. Number of colours (in the highlighter)

    b. [The amount of highlighter pen used or the amount of time the experiment was conducted for.[1]][The brand of highlighter pen used or the type of paper used in the experiment.[2]]

- ✓ ✗ I have identified one controlled variable.[1]
- ✓ ✗ I have identified a second controlled variable.[2]

12D Experimental factors affecting data

Progress questions

1. A. Spilling a solution is not a systematic but a random error.
2. C. Parallax is a systematic error.
3. B. Random errors do not affect results in consistent ways.

4. A. Precise data are within close proximity of each other.

5. C. Values that are accurate are close to the theoretical value.

6. A. Reproducibility describes results collected by different experimenters under changed conditions.

7. D. Results can be repeated under the same conditions by the same experimenters.

8. C. The zeros after the first significant figure are considered significant.

9. A. Addition requires answers to be expressed to the lowest number of decimal points in the calculation.

10. A. Multiplication requires answers to be expressed to the least number of significant figures (0.51 g has 2 sig. figs) in the calculation.

11. D. In an experiment, only the independent variable should be changed.

Deconstructed

12. C **13.** D

14. [For the experiment to be valid, all variables outside the independent variable should be controlled.[1]][For this experiment, the independent variable is the conditions in which the banana was kept (inside container vs outside container.[2]][Despite this, many other variables were also changed in the experiment. This included the size of the bananas and the time intervals between measurements.[3]][Therefore, the conclusion is not particularly valid, as other variables may have affected the results obtained.[4]]

- ✓ ✗ I have identified the parameters of validity.[1]
- ✓ ✗ I have identified the independent variable.[2]
- ✓ ✗ I have identified the changes in other variables.[3]
- ✓ ✗ I have linked my answer to the question.[4]

Exam-style

15. [Systematic error.[1]][Random error.[2]][Parallax error.[3]][Mistake or personal error.[4]]

- ✓ ✗ I have connected an error to the uncalibrated thermometer.[1]
- ✓ ✗ I have connected an error to the loss of reagent.[2]
- ✓ ✗ I have connected an error to the meniscus.[3]
- ✓ ✗ I have connected a mistake to the reagent.[4]

16. a. Tests 1, 2 and 4.

b. [It was expected that the results would be around 15.00 mL of HCl.[1]][However, most of the results collected were much higher than this value.[2]][Although there was one result that would be considered accurate, the average of all the concordant results (Test numbers 1, 2, and 4) was 18.85 mL, which is still higher than the true value.[3]][Therefore, the results are not very accurate, but are precise, so a systematic error may have been present.[4]]

- ✓ ✗ I have identified the expected results.[1]
- ✓ ✗ I have identified the main difference between the expected and actual results.[2]
- ✓ ✗ I have described the the data collected.[3]
- ✓ ✗ I have linked my answer to the question.[4]

c. Two

17. a. [Accessibility of reagents.[1]][The quantity of reagents available for testing.[2]]

- ✓ ✗ I have identified one limitation associated with the experiment.[1]
- ✓ ✗ I have identified a second limitation associated with the experiment.[2]

b. [Reproducibility is a measure of how close results are of the same experiment being conducted in a different environment by different experimenters.[1]][Due to the fact the results obtained in the experiments were different,[2]][the experiment is not considered to be very reproducible.[3]]

- ✓ ✗ I have defined reproducibility.[1]
- ✓ ✗ I have identified the key difference between the experiments.[2]
- ✓ ✗ I have linked my answer to the question.[3]

c. The reproducibility can be improved through the use of more precise equipment.

d. [Reproducibility describes the ability of results to be replicated using the same method conducted in different conditions by different experimenters.[1]][However, repeatability measures the ability of results to be replicated when conducted under the same conditions by the same experimenter.[2]]

- ✓ ✗ I have defined reproducibility.[1]
- ✓ ✗ I have compared reproducibility to repeatability.[2]

18. B. A systematic error would affect all the results by the same amount so the line would not be kinked.

19. A. Precise results may be biased, because even though they are close together, they may have been obtained from a preferred sample and not reflect the true characteristics of the substance under analysis. Sensitive instruments should give more accurate measurements, but may be subject to random error associated with environmental fluctuations. The method must also be appropriate for the analysis to be valid. Repeating a procedure using the same equipment will not remove the uncertainty associated with systematic errors. Systematic errors are consistent repeatable errors associated with faulty equipment or flaws in experimental method or design.

20. a. % of fat in the chocolate.

b. Chocolate sample with no fat.

c. As the % of fat in the chocolate increases, the melting temperature decreases.

d. Three

21. a. The change in blood glucose levels.

b. If the sugar content in food is increased, then blood glucose levels will likely increase.

c. [Thomas's glucose metre was consistently measuring the glucose levels 0.20 mmol L^{-1} less than the true value, likely underestimating the true sugar content of each snack.[1]] [This would decrease the accuracy of his results and is a systematic error.[2]]

I have identified the key factor affecting the results.[1]

I have linked my answer to the question.[2]

12E Writing scientific material

Progress questions

1. D. Models have limitations.

2. C. The image names the three different types of heat transfer.

3. C. Common terminology supports the understanding of both simple and complex processes.

4. A. Some units like mol can be used in many different types of calculations.

5. D. Volume is commonly measured in both litres and metres cubed.

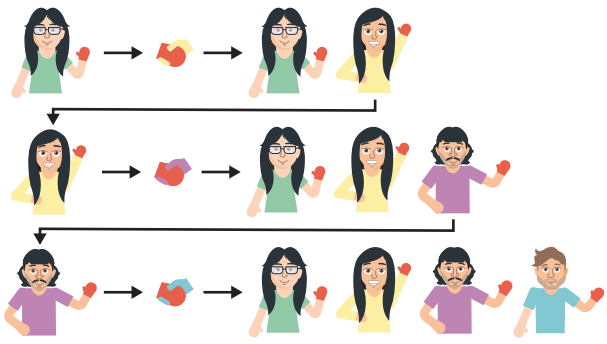
6. A. Where possible, the writing should be accessible to lots of different readers.

7. A scientific report must be based on evidence (data) to be considered scientific.

Deconstructed

8. B **9.** C

10.



Exam-style

11. a. Different colours of light have different wavelengths/patterns.

b. Nanometres (nm)

c. We are unable to see why each colour has a different wavelength.

12. The size of the atoms or molecules or size of bond length or exact shape or amount of space between atoms.

13. C. L is Litres which is used when measuring the volume of a liquid.

M is Molarity of solution in mol L^{-1}.

N is a Newton, which is used to measure forces in physics, not to be confused with N_A which is the Avogadro constant.

K is Kelvin, which is used to measure temperature.

14. a. Months

b. Test A

c. The length of carrot

15. a. Size of rock used

b. To test the effect of the use of different sized rocks on the size of crystals that are able to grow

c. Title, introduction, methodology and methods, results, discussion, conclusion, and references

Chapter 12 review

Multiple choice

1. A. Qualitative data is based on descriptive information.

2. B. In this experiment, the relationship between the independent and dependent variables is correlated (as long as the experiment is appropriately controlled).

3. C. The purpose of an investigation is stated in the introduction.

4. D. Solvents are often volatile; in order to minimise the risk of inhaling the fumes, ventilation is important.

5. C. Controls show that any changes in the dependent variable were due to the independent variable and cannot improve the accuracy of the results.

6. B. Errors in reading measuring equipment affect all readings in the same way; however, results can still be measured as being close to each other.

7. B. There are factors that can limit the ability of an experiment to be conducted. Mistakes and errors are not considered as limitations.

8. D. SDS provides information regarding the hazards of substances and techniques used.

9. C. Random errors are unpredictable and occur irregularly.

10. C. All variables except the independent and dependent variable need to be controlled.

11. D. Data represented in a graph shows a pattern between the independent and dependent variable.

12. B. Precise data are within close proximity of each other.

13. D. Bias in an experimental investigation would be related to situations where the method of investigation or interpretation of results is managed/influenced to produce preferred data. The validity of an experimental investigation is related to the experimental method and how appropriate it is in addressing the aim of the investigation. The accuracy of an experimental investigation refers to agreement between the outcome of an investigation and the true value. None of these attributes (bias, validity or accuracy) is improved by repeating the investigation multiple times. When an experiment is repeated multiple times using the same method and equipment each time could reduce the amount of random errors, which improves precision. An investigation can be precise without providing an accurate outcome, for example, if the experimental method was not valid.

14. A. Precise results may be biased because even though they are close together they may have been obtained from a preferred sample and not reflect the true characteristics of the substance under analysis. Sensitive instruments should give more accurate measurements, but may be subject to random error associated with environmental fluctuations. The method must be appropriate for the analysis to be valid. Repeating a procedure using the same equipment will not remove the uncertainty associated with systematic errors. Systematic errors are consistent repeatable errors associated with faulty equipment or flaws in experimental method or design.

15. B. The only alternative that could increase accuracy.

Short answer

16. a. Amount of cornflour or amount of water

b. Qualitative data

c. [As shown in the table, every sample contains a different amount of cornflour and water.[1]][The experimenter has changed multiple variables (cornflour and water); therefore, the results are not valid.[2]]

- ✓ ✗ I have identified the change in multiple variables.[1]
- ✓ ✗ I have identified the relationship between changing variables and validity.[2]

17. a. It is expected that the extra tax placed on unhealthy foods would encourage people to consume healthier food(s).

b. [The taxes placed on unhealthy foods would mean that the foods would cost more to purchase.[1]][As a result, people would be less likely to buy these foods, leading to a decrease in the consumption of unhealthy foods.[2]]

- ✓ ✗ I have identified the impact of taxes on food prices.[1]
- ✓ ✗ I have described the effect of taxes on the consumption of unhealthy foods.[2]

c. [By increasing food prices, this could make it more difficult for people to afford and access foods.[1]][This could have the opposite effect, where people could become less healthy due to not being able to eat enough food.[2]][Additionally, introducing this tax is effectively trying to influence human behaviour, meaning the government would be making decisions regarding what people can and cannot access. This could be considered highly unethical.[3]]

- ✓ ✗ I have identified the impact of taxes on food accessibility.[1]
- ✓ ✗ I have identified an adverse impact on individual health.[2]
- ✓ ✗ I have described an ethical concern related to the government influencing human behaviour.[3]

18. a. A bubble solution that does not contain any additional substances (contains only water)

b. i. Bar graph

ii. Corn syrup

iii. [Reproducibility measures the ability of an experiment to collect similar results when conducted by different experimenters.[1]][In this experiment, there is a lot of variability in the way that the data is collected. For example, when taking the photo that is used to measure bubble size, the positioning of the experimenter relative to the bubbles could impact the size of the bubbles measured.[2]][Considered the results recorded for both glycerin and corn syrup are relatively close to each other, this could affect the overall conclusion of the experiment.[3]][Also, the concentration of the solutions and the size of the wand were not included; therefore, the experiment cannot be replicated properly.[4]][As a result, the results are not very reproducible.[5]]

- ✓ ✗ I have defined reproducibility.[1]
- ✓ ✗ I have described an area of variability in the experiment.[2]
- ✓ ✗ I have identified an impact of the variability on the conclusion drawn.[3]
- ✓ ✗ I have described the impact of the exclusion of key information related to the materials used.[4]
- ✓ ✗ I have linked my answer to the question.[5]

iv. The use of corn syrup produces the largest bubbles, followed by glycerin and dish washing detergent.

19. a. [The law of conservation of energy states that energy is transferred or transformed, which does not mean that the energy needs to be used for a specific purpose.[1]][The energy available in the coal was still transformed into thermal energy, even if some escaped to heat up the surrounding air rather than the food.[2]][If the total energy before and after was measured, even in its different forms, it would be the same.[3]][Therefore, the student's statement is inaccurate.[4]]

- ✓ ✗ I have identified the main error in the statement relative to the law of conservation of energy.[1]
- ✓ ✗ I have described the energy change(s) during this scenario.[2]
- ✓ ✗ I have identified a strategy that can be used to confirm the law of conservation of energy.[3]
- ✓ ✗ I have linked my answer to the question.[4]

b. i. Being able to measure the energy lost to the environment

Alternate answers:

- Being able to measure the energy transferred into the food
- Being able to measure the chemical energy in the coal
- The availability of coal/food for the experiment

ii. [The type of coal used or the type of food used.[1]] [The barbecue used or the distance between the food and the coal.[2]][The length of time of cooking/burning coal.[3]]

I have listed one variable that needs to be controlled.[1]

I have listed a second variable that needs to be controlled.[2]

I have listed a third variable that needs to be controlled.[3]

20. a. The concentration of vinegar used

b. i. [This test is being conducted on humans,[1]][where the effect of the experiment may cause the subjects some discomfort.[2]]

I have identified a key ethical consideration.[1]

I have identified the effect of conducting research in this way.[2]

ii. [Since the results were derived from many different individuals, the self rating used is subjective and would be based on the previous experiences of each subject.[1]] [As a result, the interpretation of the results would vary between subjects.[2]][Facial expressions from each subject in response to eating lemon would not be an accurate indicator of sourness as this would also vary between subjects and their experiences.[3]][Therefore, the results from this experiment are not valid.[4]]

I have identified the subjectivity of the self rating system.[1]

I have identified the impact of the self rating system.[2]

I have described the subjective nature of the use of facial expressions.[3]

I have linked my answer to the question.[4]

iii. There is no direct relationship between the concentration of vinegar consumed and a person's reaction when subsequently consuming lemons.

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Glossary

^{13}C-NMR spectroscopy analytical technique that uses electromagnetic radiation and magnetic fields to provide information about the number of non-equivalent carbon environments in an organic compound p. 453

^{13}C-NMR spectrum spectrum of chemical shift values in ppm relative to a chemical standard (usually TMS) p. 453

^{1}H-NMR (proton NMR) spectroscopy analytical technique that uses electromagnetic radiation and magnetic fields to provide information about the number of non-equivalent proton environments in an organic compound and the number of protons in those environments p. 462

^{1}H-NMR spectrum spectrum of chemical shift values in ppm relative to a chemical standard (usually TMS) p. 462

2-amino acid (α-amino acid) amino acid in which a carboxyl ($-COOH$) and an amino group ($-NH_2$) are both bonded to the second carbon atom p. 360

A

absorbance measure of the amount of light that is absorbed by a substance p. 444

accuracy how close measured values are to their true value p. 576

achiral compound compound with a superimposable mirror image p. 506

acid rain low pH rainfall, caused by waste gases from combustion containing sulfur and nitrogen oxides, which combine with atmospheric water to form acids p. 379

acidic amino acid amino acid with a carboxyl group in its side chain p. 524

acidic environment solution with a greater concentration of hydrogen ions (H^+) than hydroxide ions (OH^-) p. 98

activation energy (E_a) minimum amount of energy required for a reaction to proceed p. 28

active ingredient component of a substance or mixture that produces a chemical or biological effect p. 506

active site region of an enzyme where the substrate molecule binds to the enzyme and undergoes a chemical reaction p. 524

actual yield measurement of the amount of product that is actually produced as a result of a chemical reaction p. 379

addition reaction reaction where one molecule combines with another to form a larger molecule with no other products p. 360

additive a substance added to improve or optimise a chemical process p. 268

adsorption adhering of a component onto the stationary phase p. 474

aim purpose of an experiment p. 546

alcohol organic compound that has a hydroxyl ($-OH$) functional group bonded to a carbon atom in the parent chain p. 320

aldehyde organic compound that contains an aldehyde functional group ($-CHO$) p. 320

algae diverse group of aquatic organisms that have the ability to conduct photosynthesis p. 379

aliquot portion of a sample solution used for analysis during titration p. 415

alkane saturated hydrocarbon p. 320

alkene hydrocarbon that includes at least one carbon-carbon double bond functional group ($C=C$) p. 320

alkyl group group containing only carbon and hydrogen atoms (e.g. $-CH_3$, $-CH_2CH_3$) p. 320

amine organic compound with an amino functional group ($-NH_2$) p. 320

anecdote the communication of an abstract idea about a person, place, or thing through the use of a story or narrative p. 564

anode electrode where oxidation (loss of electrons) occurs p. 107, 260

aqueous electrolyte dissolved ionic compound with ions that are free to move (in aqueous state) p. 260

artificial photosynthesis process that utilises human-made materials to capture sunlight and split water molecules to create hydrogen and oxygen p. 291

atom economy mass of desired products divided by mass of all reactants given as a percentage conversion p. 379

B

base peak the most intense peak in a mass spectrum, which is assigned a relative abundance of 100% p. 434

basic amino acid amino acid with an amino group in its side chain p. 524

basic environment solution with a greater concentration of hydroxide ions (OH^-) than hydrogen ions (H^+) p. 98

battery device consisting of cells that convert chemical energy into electrical energy p. 280

bias difference between the average of a large set of measurements and the true value p. 576

biodiesel fuel produced by the transesterification of fats and oils in organic matter p. 12

bioethanol fuel produced by the anaerobic fermentation of glucose from organic matter p. 12

biofuel fuel sourced from organic matter p. 12

biogas gaseous fuel produced by the anaerobic breakdown of organic matter p. 12

biomass any organic material made of plant or animal matter p. 12, 379

bioplastic plastic produced from biomass p. 379

boiling point the temperature at which the vapour pressure of a liquid equals the atmospheric pressure p. 406

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C

calibrate adjust an instrument to ensure it produces accurate results p. 62

calibration curve a graphical representation of the relationship between the concentration of a substance and its corresponding response on a detector p. 474

calibration factor amount of energy (in J or kJ) required to be released/absorbed in a given calorimeter to increase/decrease water temperature by 1 °C p. 62

calorimeter insulated vessel designed to minimise and account for heat loss p. 62

carbohydrate any polymer made up of sugar monomers like glucose p. 22, 360

carbon neutral describes a fuel that does not result in a net production of carbon dioxide from sourcing and consumption p. 12

carbon-13 nucleus the nucleus of the carbon-13 isotope, which has an odd mass, allowing it to be detected by an NMR spectrometer p. 453

carboxyl group a combination of two functional groups (−COOH) attached to a single carbon atom, namely, hydroxyl (−OH) and carbonyl (C=O) groups p. 398, 320

catalyst a substance used to provide an alternate reaction pathway with a lower activation energy, thus decreasing the amount of energy required to break the bonds in the reactants, meaning a greater proportion of reactant particles have sufficient energy to collide successfully p. 185

cathode electrode where reduction (gain of electrons) occurs p. 107, 260

cell voltage voltage produced between the anode and cathode of an electrochemical cell p. 120

cellular respiration process of converting glucose into energy in the cells of living organisms p. 22

chemical decomposition processes in which larger chemical species are broken into simpler molecules p. 4, 506

chemical energy energy stored in the bonds (electrostatic attractions) of chemical compounds p. 28

chemical shift the resonant frequency of an atomic nucleus relative to a standard in a magnetic field p. 453

chiral centre carbon atom in a compound attached to four unique environments p. 506

chiral compound compound with a non-superimposable mirror image p. 506

chromatogram visual output of chromatography p. 474

circular economy continuous cycle that focuses on the optimal use and re-use of resources from the extraction of raw materials through to production of new materials, followed by the consumption and re-purposing of unused and waste materials p. 379

closed system a system in which energy can enter or leave, but matter cannot p. 172

coal combustible fossil fuel formed by the partial decay of plant and animal matter p. 4

coal seam gas natural gas sourced from coal deposits p. 4

collision theory a theoretical model that explains the rates of chemical reactions in terms of collisions between particles p. 172

combustion exothermic reaction between a fuel and oxygen gas p. 28

competitive inhibitor competes with the substrate for binding to an active site in an enzyme p. 524

complete combustion combustion reaction where oxygen is in excess, producing only carbon dioxide and water p. 28

compromise conditions conditions that may not always give the greatest yield of product, but are the most economically viable when it comes to balancing factors like cost and rate of reaction p. 243

concentration-time graph a graph of concentration versus time used to represent equilibrium reactions p. 200

concentration amount of chemical substance per unit of volume p. 415

concordant titres three or more titres that fall within 0.1 mL of each other p. 415

condensation reaction chemical reaction in which two or more molecules combine and release a water molecule p. 360

conjugate redox pair the electron donor (reactant/product) and its corresponding electron acceptor (product/reactant) p. 90

control group (controlled variables) sample that is subjected to the same conditions as all other samples without the independent variable p. 564

controlled variable(s) variable(s) held constant throughout the experiment p. 546

coulomb unit of electric charge (equal to the quantity of charge carried by a current of 1 ampere in 1 second) p. 144, 301

crude oil viscous black mixture of hydrocarbons p. 4

current a flow of charged particles (ions or electrons) p. 107

D

decarbonisation the process of reducing or eliminating carbon dioxide and other greenhouse gas emissions from industrial processes p. 243

degree of unsaturation a measure of the number of double and triple bonds in a compound p. 320

denaturation process where proteins lose their quaternary, tertiary and/or secondary structure due to factors such as pH and temperature change p. 524

dependent variable variable that is measured by the experimenter p. 546

deprotonation loss of a proton p. 524

desorption release of a component from the stationary phase by dissolving p. 474

digestion a series of complex processes involved in the breakdown of food p. 22

discharge conversion of chemical energy into electrical energy as a result of spontaneous redox reactions p. 280

dispersion forces weak intermolecular forces caused by attraction between instantaneous dipoles in adjacent molecules p. 335

distillate a liquid product condensed from gas during distillation p. 406

distillation process involving the conversion of a liquid into vapour that is then condensed back to liquid form p. 12

dynamic equilibrium the point in a reversible chemical reaction when the rate of the forward reaction is equal to the rate of the reverse reaction, and the concentrations of products and reactants is constant p. 200

E

economic considerations taking into account the associated costs of time and money p. 554

electric charge property of matter carried by current and measured in coulombs, where the charge on a single electron is -1.60×10^{-19} coulombs p. 144, 301

electrochemical cell cell involving conversions between electrical and chemical energy p. 107

electrochemical series ranking of chemical species in order of their reducing and oxidising strength p. 107

electrode electrically conductive medium p. 107

electrolyser a device or system that houses the process of electrolysis and manages the process flow of inputs and outputs p. 291

electrolyte solution, liquid, or gel containing ions p. 107

electrolytic cell cell that facilitates electrolytic (non-spontaneous redox) reactions p. 268

electrolytic half-equation one of two equations (oxidation or reduction) that describes one half of an electrolytic reaction p. 260

electrolytic reaction non-spontaneous redox reaction that requires a specified voltage from an external power source to occur p. 260

electronegativity how strongly an atom attracts electrons towards itself p. 320

electroplating application of a layer of a metal onto another metal during an electrolytic reaction p. 268

eluent solvent fluid that moves through a chromatography system p. 474

empirical formula chemical formula showing the lowest whole number ratio of the number of atoms in a compound p. 320

end point point at which a colour change occurs during titration p. 415

endothermic reaction chemical reaction that absorbs energy (in the form of heat) from the surrounding environment p. 28, 212

energy content amount of heat energy (in joules or kilojoules) produced upon burning 1 gram of a pure substance p. 22

energy profile diagram diagram that represents energy changes during a chemical reaction p. 28

energy transformation conversion of energy from one form (such as chemical, electrical, kinetic, thermal, light, or sound) to another p. 75

enhanced greenhouse effect process of the warming of the Earth's lower atmosphere due to the increased concentration of gases like carbon dioxide, water vapour and methane in the air p. 4

enthalpy change (ΔH) overall change in the chemical energy of a system p. 28

enzyme-substrate complex name for the unit which has the substrate bound to the active site of an enzyme p. 524

enzymes proteins which catalyse chemical reactions in living systems p. 360, 524

equilibrium constant (K) the value of the concentration fraction for a system at equilibrium p. 212

equilibrium expression $K = \frac{[C]^c[D]^d}{[A]^a[B]^b}$ p.212

equilibrium law the value of K is the ratio of the concentrations of the products to the concentrations of the reactants i.e. $K = \frac{[\text{products}]}{[\text{reactants}]}$ p. 212

equilibrium reaction reaction in which reactants and products are constantly being formed p. 200

equivalence point point at which the reaction has occurred as per the stoichiometric ratio of the balanced equation p. 415

equivalent carbon environments one or more carbon-13 nuclei attached to the same atom that are in identical chemical environments and are able to combine with adjacent carbon-13 nuclei to show as one peak in a spectrum p. 453

equivalent proton environments one or more protons (hydrogen nuclei) attached to the same atom that are in identical environments and are able to combine with adjacent protons to show as one set of peaks in a spectrum p. 462

error difference between the measured value and the true value p. 576

ester organic compound that contains an ester (−COOC−) functional group p. 320

esterification reaction chemical reaction between organic compounds that forms at least one ester and water as products p. 360, 524

ethical considerations taking into account the effect on other living organisms (e.g. humans and animals) p. 554

exothermic reaction chemical reaction accompanied by the release of energy (in the form of heat) p. 28, 212

extent the proportion of reactants that have been converted into products p. 200

external circuit flow of electrons through an external wire p. 107

extrapolate extend a graph to infer new values outside the range of data p. 62

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F

Faraday constant charge on one mole of charged particles, equal to 96 500 coulombs per mole p. 144, 301

fats lipid molecules that are solid at room temperature p. 360

fatty acid carboxylic acid with a long aliphatic hydrocarbon chain p. 360

feasible reaction a reaction that could occur but will not necessarily occur or be observable p. 107

feedstock raw material used for producing another product p. 12, 153, 379

fermentation breakdown of a substance in the presence of microorganisms such as yeast p. 12

fingerprint region complex absorption pattern in the region between 400 cm^{-1} and 1500 cm^{-1} that is unique to each organic compound p. 444

fossil fuel natural fuel that is formed under the Earth's crust from the decomposition of plant and/or animal remains over millions of years p. 4

fractional distillation technique used to separate liquids (fractions) with a narrow range of boiling points p. 406

fragment ion simple positively charged fragment formed from the cleavage of bonds in the molecular ion p. 434

fragmentation the process in which molecular ions undergo bond cleavage to form smaller fragments p. 434

fuel substance that is used (usually combusted) to produce energy p. 4

fuel cell electrochemical cell that continuously converts chemical energy into electrical energy via a redox reaction p. 135

functional group specific group of atoms within a compound that affects the chemical properties of the compound p. 320

G

galvanic cell electrochemical cell in which chemical energy from spontaneous redox reactions is converted into electrical energy p. 107

glucose ($C_6H_{12}O_6$) an important sugar that is absorbed into the bloodstream and transported to cells p. 22

glycogen polymer made of α-glucose used by animals to store energy p. 360

glycosidic linkage ether (−COC−) linkage that joins two sugar molecules p. 360

green chemistry set of principles aimed at reducing the use or production of harmful substances in chemical processes p. 153

green hydrogen hydrogen gas produced using renewable energy sources, such as wind or solar power, through electrolysis p. 243, 291

greenhouse gases gases that contribute to the enhanced greenhouse effect by absorbing and emitting infrared radiation from the sun p. 50

grey hydrogen hydrogen gas produced through steam methane reforming (SMR), a process that involves reacting natural gas with steam to produce hydrogen gas and carbon dioxide as a by-product p. 243

H

half-cell half of a galvanic cell where either oxidation or reduction reactions occur separated from the other half-cell p. 107

half-equation reduction or oxidation equation of a complete redox reaction p. 90

haloalkane organic compound that has one or more halogen atom (element in group 7 of the periodic table, often represented by 'X') p. 320

halogen element in group 17 of the periodic table p. 320

heat of combustion amount of heat released by the complete combustion of a substance p. 28

heterogeneous catalyst a catalyst present in a different physical state from the reactants and products p. 185

high performance liquid chromatography (HPLC) chromatography technique in which the mobile phase and sample are pumped through a tightly packed stationary phase under pressure p. 474

high resolution showing both singular peaks and distinct sets of peaks with splitting patterns p. 462

homogeneous catalyst a catalyst present in the same physical state as the reactants and products p. 185

homologous series series of organic compounds that have the same general formula and similar chemical properties p. 335

hydrocarbon compound consisting of hydrogen and carbon only p. 320

hydrogen bonding a type of permanent dipole-dipole attraction between molecules (not a covalent bond) that results from the attractive force between hydrogen atoms covalently bonded to a very electronegative atom such as an N, O, or F atom p. 335

hydrogen nucleus the nucleus of the hydrogen atom, which has an odd mass, allowing it to be detected by an NMR spectrometer p. 462

hydrolysis chemical reaction in which water reacts with a larger molecule to break it into two or more smaller molecules p. 360

hydroxyl group a functional group (−OH) with one hydrogen and one oxygen atom p. 320, 398

hypothesis testable statement which predicts the outcome of an experiment p. 546

I

immiscible describes a set of liquids that do not mix with each other p. 506

incomplete combustion combustion reaction where oxygen supply is limited; able to produce a range of carbon-based products and water p. 28

independent variable variable that is deliberately manipulated by the experimenter p. 546

indicator substance that changes colour to indicate the end point p. 415

infrared light invisible electromagnetic radiation that transmits energy p. 444

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infrared spectroscopy qualitative analytical technique that uses infrared radiation to analyse the bond vibrations, providing information about molecular structures and functional groups p. 444

infrared spectrum graph representing the absorbance of infrared light at different wavelengths within the infrared region of the electromagnetic spectrum p. 444

instantaneous dipole partial positive and negative charge that suddenly appears in an atom or molecule due to the random movement of electrons p. 335

integration curve curve on a ^{1}H-NMR spectrum showing the relative number of hydrogen atoms in a proton environment p. 462

internal circuit flow of ions through a salt bridge p. 107

interpolate infer values from a graph within the range of data p. 474

iodine value (IV) mass of iodine in grams that is consumed by 100 g of a fat or oil p. 415

irreversible reaction a reaction that can only proceed in one direction and cannot be reversed p. 200

IUPAC naming set of rules used to name organic compounds according to the International Union of Pure and Applied Chemistry (IUPAC) p. 335

K

ketone organic compound that contains a carbonyl functional group (C=O), where the carbon atom in the −C=O group is bonded to two other carbon atoms p. 320

kinetic energy the energy that a particle has due to its motion p. 172

L

LC-MS combined use of liquid chromatography and mass spectrometry p. 487

Le Chatelier's principle when a system in dynamic equilibrium is subject to a change, the system will adjust itself to partially oppose the effect of the change p. 226

legal considerations taking into account the legality of research, as well as how the research may influence the law p. 554

life cycle the management of the production, processing, storage, transportation, use, and disposal of a chemical product p. 12

limitations (models) often oversimplified, use approximations, and missing key details p. 589

lipid broad category of biomolecule commonly found in food which has two main types: fats and oils p. 360

lock-and-key model theory of enzyme-substrate binding where the substrate perfectly fits the active site of the enzyme p. 524

low resolution showing only singular peaks without splitting patterns p. 462

M

mass spectrometry analytical technique used to measure the mass-to-charge ratio of ions in a sample p. 434

mass/charge ratio (m/z) the ratio of the mass of an ion relative to its charge p. 434

medicinal molecule compound with healing properties p. 506

melting point the temperature at which the two states, liquid and solid, coexist in equilibrium p. 406

meniscus curved upper surface of liquid p. 415

metabolism chemical reactions in the body's cells that change food into energy p. 22, 360

method specific steps and techniques required to collect, visualise, and analyse experimental data in a scientific investigation p. 576

methodology different ways in which the planning and conducting of scientific investigations can be carried out p. 576

miscibility ability of two or more substances to dissolve in each other p. 474

mistake sometimes called personal errors, mistakes should not be included in reporting and analysis p. 576

mixture a substance that can be separated into two or more substances by physical means and displays the properties of the substances that it is composed of p. 406

mobile phase fluid in a chromatography system that carries the sample over the stationary phase p. 474

molar heat of combustion amount of heat, in kJ mol^{-1}, released when 1 mole of substance completely combusts in excess oxygen gas p. 28, 62

molar volume of gases volume occupied by one mole of an ideal gas at a given temperature and pressure p. 50

molecular (parent) ion peak the peak in the mass spectrum that corresponds to the molecular ion, which has the highest m/z ratio p. 434

molecular formula chemical formula that shows the number of each atom in a molecule p. 320

molecular ion the ion formed when a neutral molecule is bombarded with high-energy electrons p. 434

molecule two or more atoms covalently bonded by sharing electrons p. 320

molten electrolyte melted ionic compound with ions that are free to move (in liquid state) p. 260

monosaccharide smallest building block of carbohydrates consisting of only one sugar molecule, e.g. glucose, fructose or galactose p. 360

N

n + 1 rule the number of splits in a peak is equal to the number of hydrogen atoms in the neighbouring proton environment(s) (n) + 1 p. 462

natural gas fossil fuel consisting of small hydrocarbon molecules p. 4

non-equivalent carbon environments one or more carbon-13 nuclei attached to different atoms that are in different chemical environments p. 453

non-equivalent proton environments one or more protons (hydrogen nuclei) attached to different atoms that are in different chemical environments, causing splitting to adjacent protons p. 462

non-renewable resource resource that cannot be replaced by natural processes within a relatively short period of time p. 4

non-scientific ideas ideas that are not developed by following the scientific method p. 546

O

oils lipid molecules that are liquid at room temperature p. 360

open system a system in which both matter and energy can enter or leave p. 172

opinion a view or judgement formed about something, not necessarily based on fact or knowledge p. 564

optical isomers two non-superimposable mirror images of the same compound p. 506

optimal temperature temperature when enzyme activity is at its greatest p. 524

organic containing carbon p. 320

origin line at which samples are placed in paper and thin-layer chromatography p. 474

outlier data point or observation that differs significantly from other data points or observations p. 576

overall redox equation equation of a complete redox reaction combining reduction and oxidation half-equations p. 90

oxidation state number assigned to an atom that can be used to determine the movement of electrons in redox reactions p. 90

oxidation chemical reaction in which a chemical species loses one or more electrons p. 90

oxidised describes a chemical species that has lost one of more electrons p. 90

oxidising agent chemical species that oxidises another substance by accepting one or more electrons p. 90

P

paper chromatography chromatography technique using absorbent paper p. 474

parent chain typically the longest continuous chain of carbon-carbon bonds, depending on the functional groups present p. 335

peak area the area enclosed between the peak and the baseline on a chromatogram p. 474

percentage efficiency percentage of energy transformed to a 'useful' form or transferred to a substance p. 75

percentage yield efficiency of a chemical reaction that has taken place in terms of the amount of product actually produced compared to the predicted (theoretical) yield, which is given by $\frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$ p. 185, 379

permanent dipole-dipole attraction electrostatic force of attraction between the permanent dipoles of adjacent polar molecules p. 335

permanent dipole a permanent area of partial positive or partial negative charge on a molecule due to differences in electronegativity between atoms within a molecule p. 335

petrol liquid hydrocarbon fossil fuel purified from crude oil p. 4

petroleum complex mixture of hydrocarbons (often called crude oil) found under Earth's crust p. 4

photosynthesis process of converting light energy into chemical energy in the cells of plants, algae, and certain bacteria p. 22

photovoltaics conversion of solar energy to electrical energy using human-made materials p. 291

polarity (in electrochemical cells) overall charge of an electrode p. 268

political considerations taking into account current governmental policies, and the political environment of society more broadly p. 554

polymer electrolyte membrane (PEM) also called proton exchange membrane, uses a proton-conducting polymer membrane as the electrolyte and connects two half-cells, but prevents the mixing of different molecules p. 291

polypeptide chain chain of amino acids bonded by amide links (peptide bonds) p. 524

polysaccharide complex carbohydrate formed from the condensation of multiple monosaccharides that are joined together by glycosidic linkages p. 360

porous electrode material with many holes (pores) used in a fuel cell to maximise the ability of gaseous reactants to come into contact with the electrolyte p. 135

position of equilibrium the relative concentrations of reactants and products at equilibrium for a given chemical reaction p. 226

precision how close measured values are to each other p. 576

primary alcohol alcohol in which the hydroxyl (−OH) functional group is bonded to a carbon with only one alkyl group p. 320

primary amide organic compound that contains an amide functional group at a terminal carbon atom ($-CONH_2$) p. 320

primary cell cell that cannot be recharged p. 107

primary data original data collected firsthand by researchers p. 554

primary source source providing original data, written by the experimenter p. 546

primary structure linear sequence of covalently bonded amino acids in a polypeptide chain p. 524

proportion the percentage of species with the necessary activation energy to react in a fixed sample p. 172

protein a type of biopolymer which is essential for cell and whole organism function p. 360

protonation gain of a proton p. 524

pure substance a substance composed of one type of element or one type of compound that cannot be separated into two or more substances by physical means p. 406

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Q

qualitative analysis technique that determines a non-numerical result p. 554

qualitative data non-numerical (descriptive) data collected based on observations taken during an experiment p. 554

quantitative analysis technique that identifies the amount of substance present p. 554

quantitative data numerical data collected during experiments p. 554

quaternary structure combination of two or more interacting tertiary chains p. 524

R

racemate an approximately 50/50 mixture of a chiral compound's two optical isomers, which does not rotate polarised light in a specific direction p. 506

random error usually a 'one-off' error in measurement that differs in amount between trials p. 576

rate-time graph a graph of rate of reaction versus time used to represent equilibrium reactions p. 200

reaction pathway one or more chemical reactions designed to convert reactants into a desired product p. 185, 360

reaction quotient (*Q*) the value of the concentration fraction for a system that is not at equilibrium p. 212

reaction rate the change in concentration of a reactant or product over a period of time p. 172

recharge conversion of electrical energy into chemical energy through electrolytic reactions p. 280

redox reaction chemical reaction involving the transfer of one or more electrons between chemical species p. 90

reduced describes a chemical species that has gained one or more electrons p. 90

reducing agent chemical species that reduces another substance by donating one or more electrons p. 90

reduction chemical reaction in which a chemical species gains one or more electrons p. 90

relative abundance the abundance/intensity of an ion relative to the base peak p. 434

renewable resource resource capable of being replaced by natural processes within a relatively short period of time p. 12, 153, 379

repeatability closeness of the agreement between the results of successive measurements of the same quantity, carried out under the same conditions p. 576

reproducibility closeness of the agreement between the results of measurements of the same quantity, carried out under changed conditions p. 576

resolution (chromatography) degree of separation between two different peaks on a chromatogram p. 474

resolution (measurement) the smallest change in quantity that is measurable (by a particular instrument) p. 576

retention time (R_t) time taken for a component in a sample to pass through an HPLC column p. 474

reversible reaction a reaction that can proceed both forwards and backwards p. 200

S

safety data sheet (SDS) document that outlines the health and safety information associated with different materials and chemicals p. 554

salt bridge connection that allows the flow of ions between two half-cells to complete the circuit p. 107

saturated (organic compound) possessing only single bonds between carbon atoms p. 320

scientific ideas ideas that are developed by following the scientific method p. 546

scientific method procedure used to investigate scientific ideas p. 546

seaweed a type of macroscopic algae p. 379

secondary alcohol alcohol in which the hydroxyl (−OH) functional group is bonded to a carbon atom with two alkyl groups p. 320

secondary cell electrochemical cell that can be recharged p. 280

secondary data data that has been previously collected that is now accessible to different researchers p. 554

secondary source source that has interpreted primary sources p. 546

secondary structure arrangement of a primary protein structure in a way that results in an α-helix or β-pleated sheet due to hydrogen bonding p. 524

semi-structural (condensed) formula condensed form of a structural formula that does not show all bonds between atoms in a compound p. 320

side reaction a reaction that occurs at the same time as the main reaction, leading to the formation of side products and a lower yield of the main product p. 243

significant figures number of digits required to express a number to a certain level of accuracy p. 576

simple distillation technique used to separate liquids with significantly different boiling points p. 406, 506

skeletal formula representation of a molecular structure where covalent bonds are shown as lines, carbon atoms are shown as vertices, and hydrogen atoms bonded to carbon atoms are not shown p. 320

social considerations taking into account the effect on society p. 554

solution calorimetry use of a calorimeter to estimate the enthalpy change of a reaction that occurs in solution p. 62

solvent extraction method of separating compounds based on a difference in solubility in two solvents p. 506

specific heat capacity energy (J) required to raise the temperature of 1 gram of a given substance by 1 °C p. 62

splitting pattern the number of peaks shown in a set of peaks corresponding to a single non-equivalent proton environment p. 462

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standard electrode potential (E^0) potential of a half-cell reaction, given in volts (V), relative to the Standard Hydrogen Electrode p. 120, 268

standard hydrogen electrode standard $H^+(aq)/H_2(g)$ half-cell with standard electrode potential 0.00 V, which the electrochemical series is created with respect to p. 120

standard laboratory conditions (SLC) set of conditions used as a standard, involving a temperature of 25 °C (298 K) and a pressure of 100 kPa p. 50

standardised solution solution of known concentration p. 415

starch polymer made of α-glucose used as an energy source by animals p. 360

stationary phase solid onto which the components of a sample adsorb p. 474

steam distillation distillation by injection of water vapour to lower the boiling point of substances and thus minimise decomposition p. 506

stoichiometry the relationship between relative quantities of reactants and products in a chemical reaction p. 50

structural formula representation of a molecule that shows all the atoms and bonds in an atom or compound p. 320

structural isomers molecules with the same molecular formula but different spatial arrangement of atoms p. 335

substitution reaction chemical reaction where an atom, or group of atoms in a compound, is replaced by another atom, or group of atoms p. 360

substrate molecule which an enzyme acts upon p. 524

surface area the total area of all particles available for collisions with other reactants p. 172

Sustainable Development Goals set of 17 objectives to promote a positive present and future for people and the planet p. 153

sustainable can be produced at a rate that is greater than or equal to the rate of consumption without compromising future generations p. 4, 153

symmetrical made up of exactly identical parts facing each other or around an axis p. 453

systematic error error in measurement by the same amount in the same direction every time which also includes errors that are inherent in the experiment p. 576

systematic name standardised name used to identify organic compounds p. 335

T

temperature-time graph graph that plots change in temperature over time (particularly for a calorimetry experiment) p. 62

terminal carbon carbon atom at the end of the carbon parent chain p. 320

tertiary alcohol alcohol in which the hydroxyl (−OH) functional group is bonded to a carbon with three alkyl groups p. 320

tertiary structure overall three-dimensional structure of a protein p. 524

theoretical yield expected amount of a product produced in a chemical reaction given the quantities and stoichiometric ratios of the reactants p. 200, 379

thermochemical equation balanced chemical equation that includes the enthalpy change (ΔH) of the reaction, measured in kJ mol^{-1} or kJ p. 28

thin-layer chromatography chromatography technique using a thin stationary phase supported by an inert backing p. 474

titration quantitative technique used to find the concentration and/or amount of substance in a solution p. 415

titre volume of the solution delivered from the burette to reach the end point of a titration p. 415

transesterification reaction a type of chemical reaction used to produce biodiesel and glycerol p. 12, 360

transmittance measure of the amount of light that passes through a substance p. 444

triglyceride fat or oil composed of three fatty acid tails and a glycerol backbone p. 12

U

uncertainty level of doubt regarding the data obtained (for VCE purposes, we are only looking at this from a qualitative perspective) p. 576

unsaturated (organic compound) possessing at least one double or triple bond between carbon atoms p. 320

useful energy proportion of total energy that can be used for the desired purpose p. 75

V

valence electron number number of electrons in the outer (valence) shell of an atom p. 320

validity whether the experiment and its components including the results address the aim and hypothesis of the research p. 576

vapour pressure the pressure exerted by the vapour in equilibrium with the liquid phase at a given temperature p. 406

variable any factor (e.g. substance, condition, property) that is capable of changing throughout an experiment p. 546

viscosity resistance of a substance to flow p. 335

volatile readily converted into a gas p. 406

voltage (V) the potential difference in energy per unit charge between two points p. 120

volumetric analysis quantitative analytical technique used to determine unknown concentrations of solutions p. 415

wave number the reciprocal of the wavelength of light measured in cm^{-1} p. 444

yeast variety of microorganism which converts glucose into ethanol p. 12

yield the mass of product obtained during a chemical reaction p. 200

Z

zwitterion neutral molecule that has a positively charged $-NH_3^+$ and a negatively charged $-COO^-$ on the number two carbon

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Data book

For your Year 12 chemistry exam, you will be given a VCE Data Book that contains lots of useful information that you can use to help ace the exam. We thought it would be a good idea to get you familiar with some of the information that was in the old VCE Data Book. Have fun!

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Periodic table of the elements

1 **H** 1 0 hydrogen																	**2** **He** 4 0 helium
3 **Li** 6 9 lithium	**4** **Be** 9 0 beryllium											**5** **B** 10 8 boron	**6** **C** 12 0 carbon	**7** **N** 14 0 nitrogen	**8** **O** 16 0 oxygen	**9** **F** 19 0 fluorine	**10** **Ne** 20 2 neon
11 **Na** 23 0 sodium	**12** **Mg** 24 3 magnesium											**13** **Al** 27 0 aluminium	**14** **Si** 28 1 silicon	**15** **P** 31 0 phosphorus	**16** **S** 32 1 sulfur	**17** **Cl** 35 5 chlorine	**18** **Ar** 39 9 argon
19 **K** 39 1 potassium	**20** **Ca** 40 1 calcium	**21** **Sc** 45 0 scandium	**22** **Ti** 47 9 titanium	**23** **V** 50 9 vanadium	**24** **Cr** 52 0 chromium	**25** **Mn** 54 9 manganese	**26** **Fe** 55 8 iron	**27** **Co** 58 9 cobalt	**28** **Ni** 58 7 nickel	**29** **Cu** 63 5 copper	**30** **Zn** 65 4 zinc	**31** **Ga** 69 7 gallium	**32** **Ge** 72 6 germanium	**33** **As** 74 9 arsenic	**34** **Se** 79 0 selenium	**35** **Br** 79 9 bromine	**36** **Kr** 83 8 krypton
37 **Rb** 85 5 rubidium	**38** **Sr** 87 6 strontium	**39** **Y** 88 9 yttrium	**40** **Zr** 91 2 zirconium	**41** **Nb** 92 9 niobium	**42** **Mo** 96 0 molybdenum	**43** **Tc** (98) technetium	**44** **Ru** 101 1 ruthenium	**45** **Rh** 102 9 rhodium	**46** **Pd** 106 4 palladium	**47** **Ag** 107 9 silver	**48** **Cd** 112 4 cadmium	**49** **In** 114 8 indium	**50** **Sn** 118 7 tin	**51** **Sb** 121 8 antimony	**52** **Te** 127 6 tellurium	**53** **I** 126 9 iodine	**54** **Xe** 131 3 xenon
55 **Cs** 132 9 caesium	**56** **Ba** 137 3 barium	**57–71** lanthanoids	**72** **Hf** 178 5 hafnium	**73** **Ta** 180 9 tantalum	**74** **W** 183 8 tungsten	**75** **Re** 186 2 rhenium	**76** **Os** 190 2 osmium	**77** **Ir** 192 2 iridium	**78** **Pt** 195 1 platinum	**79** **Au** 197 0 gold	**80** **Hg** 200 6 mercury	**81** **Tl** 204 4 thallium	**82** **Pb** 207 2 lead	**83** **Bi** 209 0 bismuth	**84** **Po** (210) polo ium	**85** **At** (210) astatine	**86** **Rn** (222) radon
87 **Fr** (223) francium	**88** **Ra** (226) radium	**89–103** actinoids	**104** **Rf** (261) rutherfordium	**105** **Db** (262) dubnium	**106** **Sg** (266) seaborgium	**107** **Bh** (264) bohrium	**108** **Hs** (267) hassium	**109** **Mt** (268) meitnerium	**110** **Ds** (271) darmstadtium	**111** **Rg** (272) roentgenium	**112** **Cn** (285) copernicium	**113** **Nh** (280) nihonium	**114** **Fl** (289) flerovium	**115** **Mc** (289) moscovium	**116** **Lv** (292) livermorium	**117** **Ts** (294) tennessine	**118** **Og** (294) oganesson

atomic number — relative atomic mass — **79** **Au** 197 0 gold — symbol of element — name of element

57 **La** 138 9 lanthanum	**58** **Ce** 140 1 cerium	**59** **Pr** 140 9 praseodymium	**60** **Nd** 144 2 neodymium	**61** **Pm** (145) promethium	**62** **Sm** 150 4 samarium	**63** **Eu** 152 0 europium	**64** **Gd** 157 3 gadolinium	**65** **Tb** 158 9 terbium	**66** **Dy** 162 5 dysprosium	**67** **Ho** 164 9 holmium	**68** **Er** 167 3 erbium	**69** **Tm** 168 9 thulium	**70** **Yb** 173 1 ytterbium	**71** **Lu** 175 0 lutetium

89 **Ac** (227) actinium	**90** **Th** 232 0 thorium	**91** **Pa** 231 0 protactinium	**92** **U** 238 0 uranium	**93** **Np** (237) neptunium	**94** **Pu** (244) plutonium	**95** **Am** (243) americium	**96** **Cm** (247) curium	**97** **Bk** (247) berkelium	**98** **Cf** (251) californium	**99** **Es** (252) einsteinium	**100** **Fm** (257) fermium	**101** **Md** (258) mendelevium	**102** **No** (259) nobelium	**103** **Lr** (262) lawrencium

The value in brackets indicates the mass number of the longest-lived isotope.

Electrochemical series

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(1)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	–0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	–0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	–0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	–0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	–0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	–0.44
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	–1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	–1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	–2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	–2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	–2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	–2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	–3.04

Chemical relationships

Name	Formula
number of moles of a substance	$n = \frac{m}{M}; \quad n = cV; \quad n = \frac{V}{V_m}$
universal gas equation	$pV = nRT$
calibration factor (CF) for bomb calorimetry	$\text{CF} = \frac{VIt}{\Delta T}$
heat energy released in the combustion of a fuel	$q = mc\Delta T$
enthalpy of combustion	$\Delta H = \frac{q}{n}$
electric charge	$Q = It$
number of moles of electrons	$n(e^-) = \frac{Q}{F}$
% atom economy	$\frac{\text{molar mass of desired product}}{\text{molar mass of all reactants}} \times \frac{100}{1}$
% yield	$\frac{\text{actual yield}}{\text{theoretical yield}} \times \frac{100}{1}$

Physical constants and standard values

Name	Symbol	Value
Avogadro constant	N_A or L	6.02×10^{23} mol^{-1}
charge on one electron (elementary charge)	e	-1.60×10^{-19} C
Faraday constant	F	96 500 C mol^{-1}
molar gas constant	R	8.31 J mol^{-1} K^{-1}
molar volume of an ideal gas at SLC (25 °C and 100 kPa)	V_m	24.8 L mol^{-1}
specific heat capacity of water	c	4.18 kJ kg^{-1} K^{-1} or 4.18 J g^{-1} K^{-1}
density of water at 25 °C	d	997 kg m^{-3} or 0.997 g mL^{-1}

Unit conversions

Measured value	Conversion
0 °C	273 K
100 kPa	750 mm Hg or 0.987 atm
1 litre (L)	1 dm^3 or 1×10^{-3} m^3 or 1×10^3 cm^3 or 1×10^3 mL

Metric (including SI) prefixes

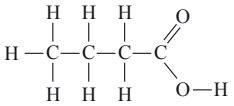
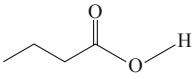
Metric (including SI) prefixes	Scientific notation	Multiplying factor
giga (G)	10^9	1 000 000 000
mega (M)	10^6	1 000 000
kilo (k)	10^3	1000
deci (d)	10^{-1}	0.1
centi (c)	10^{-2}	0.01
milli (m)	10^{-3}	0.001
micro (μ)	10^{-6}	0.000001
nano (n)	10^{-9}	0.000000001
pico (p)	10^{-12}	0.000000000001

Acid-base indicators

Name	pH range	Colour change from lower pH to higher pH in range
thymol blue (1st change)	1.2–2.8	red → yellow
methyl orange	3.1–4.4	red → yellow
bromophenol blue	3.0–4.6	yellow → blue
methyl red	4.4–6.2	red → yellow
bromothymol blue	6.0–7.6	yellow → blue
phenol red	6.8–8.4	yellow → red
thymol blue (2nd change)	8.0–9.6	yellow → blue
phenolphthalein	8.3–10.0	colourless → pink

Representations of organic molecules

The following table shows different representations of organic molecules, using butanoic acid as an example.

Formula	Representation
molecular formula	$C_4H_8O_2$
structural formula	
semi-structural (condensed) formula	$CH_3CH_2CH_2COOH$ or $CH_3(CH_2)_2COOH$
skeletal structure	

Formulas of some fatty acids

Name	Formula	Semi-structural formula
lauric	$C_{11}H_{23}COOH$	$CH_3(CH_2)_{10}COOH$
myristic	$C_{13}H_{27}COOH$	$CH_3(CH_2)_{12}COOH$
palmitic	$C_{15}H_{31}COOH$	$CH_3(CH_2)_{14}COOH$
palmitoleic	$C_{15}H_{29}COOH$	$CH_3(CH_2)_4CH_2CH{=}CHCH_2\,(CH_2)_5CH_2COOH$
stearic	$C_{17}H_{35}COOH$	$CH_3(CH_2)_{16}COOH$
oleic	$C_{17}H_{33}COOH$	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$
linoleic	$C_{17}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$
linolenic	$C_{17}H_{29}COOH$	$CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6COOH$
arachidic	$C_{19}H_{39}COOH$	$CH_3(CH_2)_{17}CH_2COOH$
arachidonic	$C_{19}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_3CH{=}CH(CH_2)_3COOH$

Heats of combustion of common fuels

The heats of combustion in the following table are calculated at SLC (25 °C and 100 kPa) with combustion products being CO_2 and H_2O. Heat of combustion may be defined as the heat energy released when a specified amount of a substance burns completely in oxygen and is, therefore, reported as a positive value, indicating a magnitude. Enthalpy of combustion, ΔH, for the substances in this table would be reported as negative values, indicating the exothermic nature of the combustion reaction.

Fuel	Formula	State	Heat of combustion ($kJ\ g^{-1}$)	Molar heat of combustion ($kJ\ mol^{-1}$)
hydrogen	H_2	gas	141	282
methane	CH_4	gas	55.6	890
ethane	C_2H_6	gas	51.9	1560
propane	C_3H_8	gas	50.5	2220
butane	C_4H_{10}	gas	49.7	2880
octane	C_8H_{18}	liquid	47.9	5460
ethyne (acetylene)	C_2H_2	gas	49.9	1300
methanol	CH_3OH	liquid	22.7	726
ethanol	C_2H_5OH	liquid	29.6	1360

Heats of combustion of common blended fuels

Blended fuels are mixtures of compounds with different mixture ratios and, hence, determination of a generic molar enthalpy of combustion is not realistic. The values provided in the following table are typical values for heats of combustion at SLC (25 °C and 100 kPa) with combustion products being CO_2 and H_2O. Values for heats of combustion will vary depending on the source and composition of the fuel.

Fuel	State	Heat of combustion ($kJ\ g^{-1}$)
kerosene	liquid	46.2
diesel	liquid	45.0
natural gas	gas	54.0

Energy content of food groups

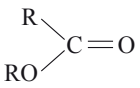
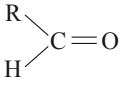
Food	Heat of combustion ($kJ\ g^{-1}$)
fats and oils	37
protein	17
carbohydrate	16

Characteristic ranges for infra-red absorption

Bond	Wave number (cm^{-1})	Bond	Wave number (cm^{-1})
C–Cl (chloroalkanes)	600–800	C=O (ketones)	1680–1850
C–O (alcohols, esters, ethers)	1050–1410	C=O (esters)	1720–1840
C=C (alkenes)	1620–1680	C–H (alkanes, alkenes, arenes)	2850–3090
C=O (amides)	1630–1680	O–H (acids)	2500–3500
C=O (aldehydes)	1660–1745	O–H (alcohols)	3200–3600
C=O (acids)	1680–1740	N–H (amines and amides)	3300–3500

^{13}C-NMR data

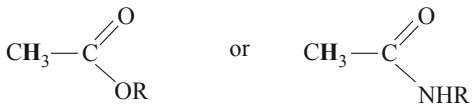
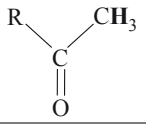
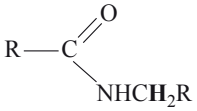
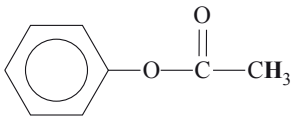
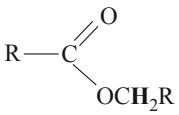
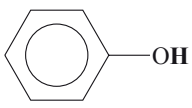
Typical ^{13}C shift values relative to TMS = 0
These can differ slightly in different solvents.

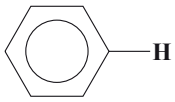
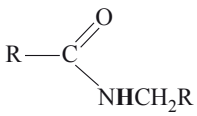
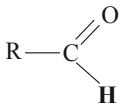
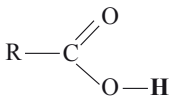
Type of carbon	Chemical shift (ppm)
$R–CH_3$	8–25
$R–CH_2–R$	20–45
$R_3–CH$	40–60
$R_4–C$	36–45
$R–CH_2–X$	15–80
$R_3C–NH_2$, $R_3C–NR$	35–70
$R–CH_2–OH$	50–90
$RC{\equiv}CR$	75–95
$R_2C{=}CR_2$	110–150
RCOOH	160–185
	165–175
	190–200
$R_2C{=}O$	205–220

^{1}H-NMR data

Typical proton shift values relative to TMS = 0

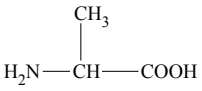
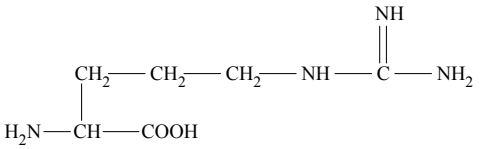
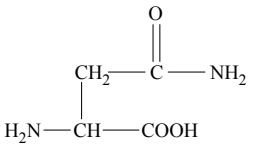
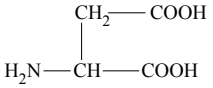
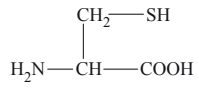
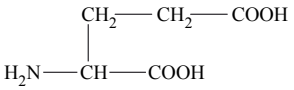
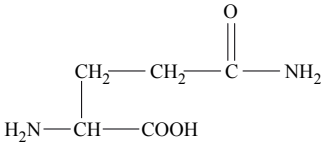
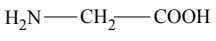
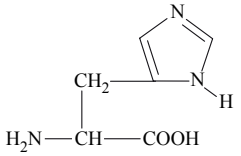
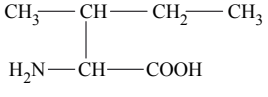
These can differ slightly in different solvents. The shift refers to the proton environment that is indicated in bold letters in the formula.

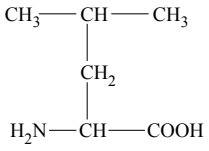
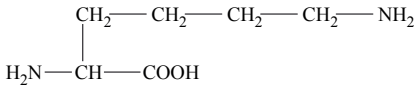
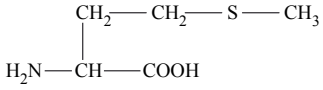
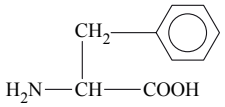
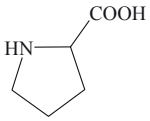
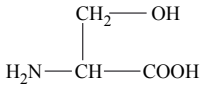
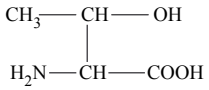
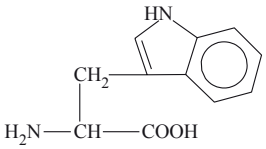
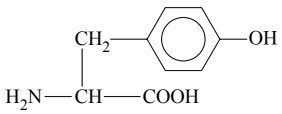
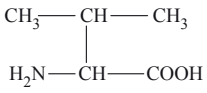
Type of proton	Chemical shift (ppm)
R–C**H**$_3$	0.9–1.0
R–C**H**$_2$–R	1.3–1.4
RCH=CH–C**H**$_3$	1.6–1.9
R$_3$–C**H**	1.5
	2.0
	2.1–2.7
R–C**H**$_2$–X (X = F, Cl, Br or I)	3.0–4.5
R–C**H**$_2$–OH, R$_2$–C**H**–OH	3.3–4.5
	3.2
R—O—C**H**$_3$ or R—O—C**H**$_2$R	3.3–3.7
	2.3
	3.7–4.8
R–O–**H**	1–6 (varies considerably under different conditions)
R–N**H**$_2$	1–5
RHC=C**H**R	4.5–7.0
	4.0–12.0

Type of proton	Chemical shift (ppm)
	6.9–9.0
	8.1
	9.4–10.0
	9.0–13.0

2-amino acids (*α*-amino acids)

The table below provides simplified structures to enable the drawing of zwitterions, the identification of products of protein hydrolysis and the drawing of structures involving condensation polymerisation of amino acid monomers.

Name	Symbol	Structure
alanine	Ala	
arginine	Arg	
asparagine	Asn	
aspartic acid	Asp	
cysteine	Cys	
glutamic acid	Glu	
glutamine	Gli	
glycine	Gly	
histidine	His	
isoleucine	Ile	

Name	Symbol	Structure
leucine	Leu	
lysine	Lys	
methionine	Met	
phenylalanine	Phe	
proline	Pro	
serine	Ser	
threonine	Thr	
tryptophan	Trp	
tyrosine	Tyr	
valine	Val	

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