Edrolo

VCE PHYSICS

Units 1 & 2

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Our mission is simple: to improve education.

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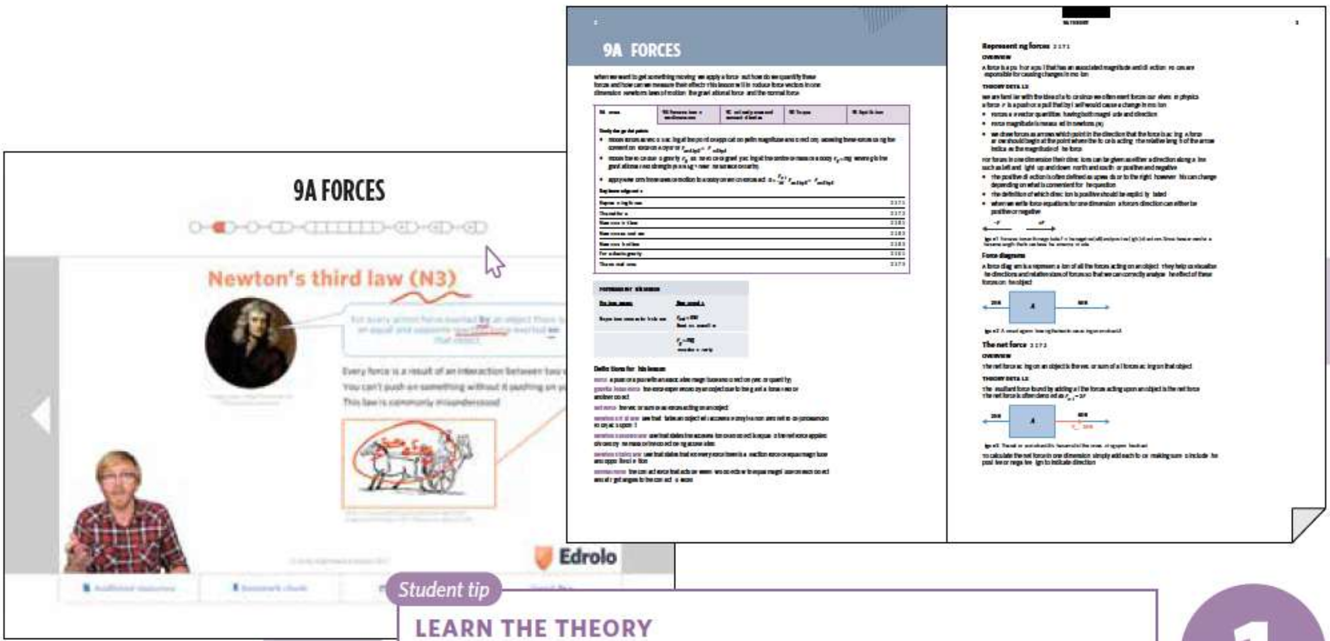
CONTENTS

USING THIS RESOURCE TO TEACH AND LEARN



Student tip

LEARN THE THEORY

Every dot-point in your study design is covered in our video lessons and textbook theory – perfect to use for pre-learning, during class, and as revision.

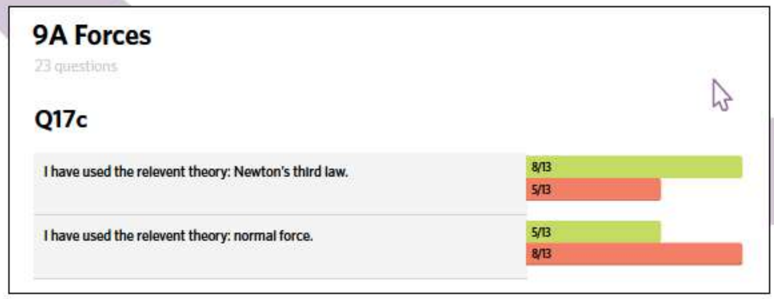
1

Teacher tip

EVALUATE STRENGTHS AND AREAS FOR IMPROVEMENT

Teachers see class-level data and individual student responses – use this to provide feedback, differentiate student learning, plan future lessons, and inform the revision program of your students.

4



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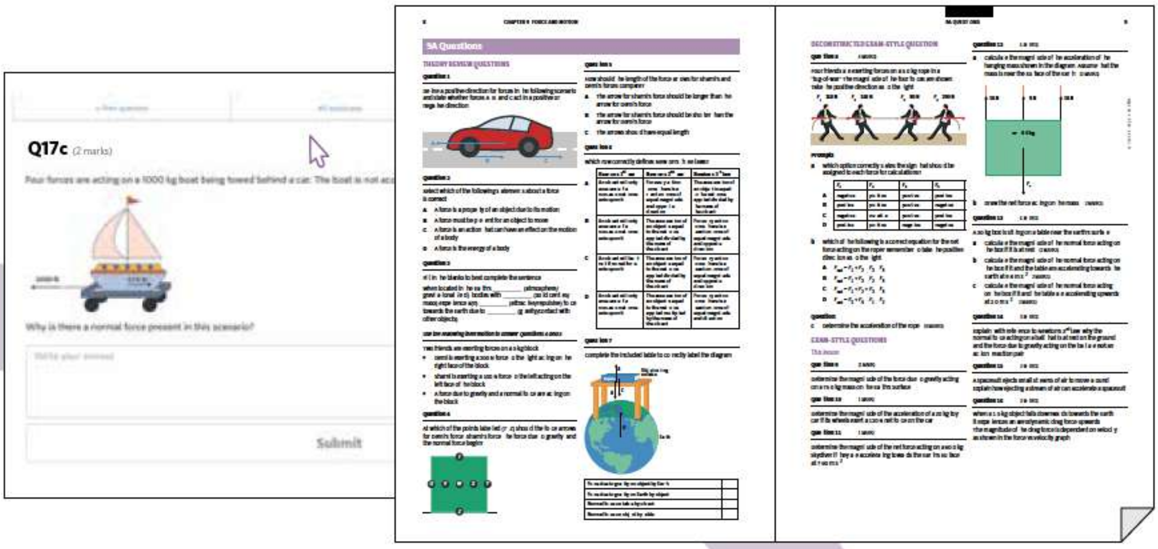


2

Student tip

CHECK FOR UNDERSTANDING

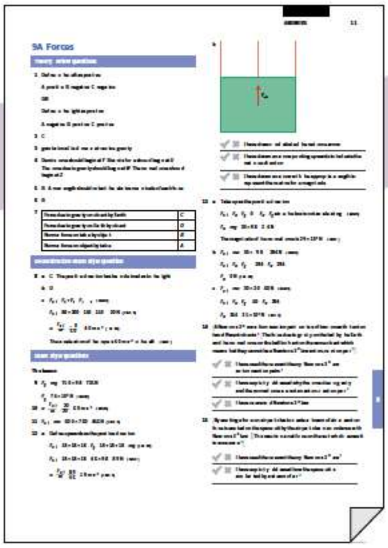
Each lesson has theory review questions, a deconstructed exam-style question, and exam-style questions so you can apply your knowledge in different ways and consolidate your learning. You'll also find tests/exams within each area of study.

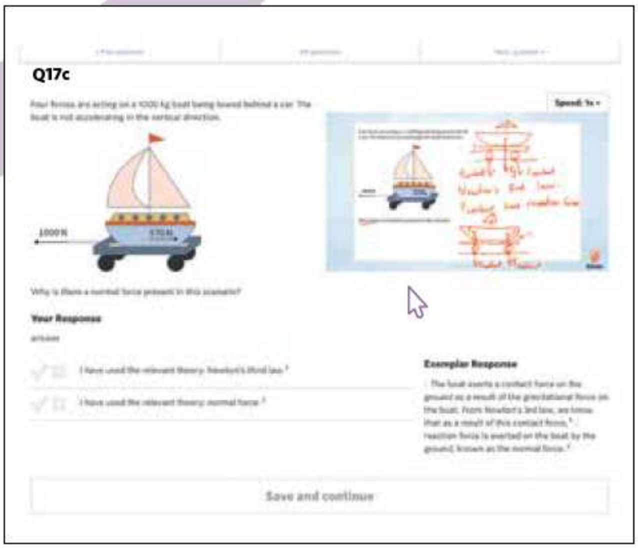
3

Student tip

SELF-ASSESS AND GET FEEDBACK

At the back of your textbook you'll find exemplar responses and checklists for every exam-style question. In your Edrolo account, you'll find video solutions as well as the interactive checklists and exemplar responses. Use these answers to target your revision and get the greatest impact from your study time. This enables you to focus on the parts of the theory you struggled with, and ask your teacher for support if you get totally stuck!





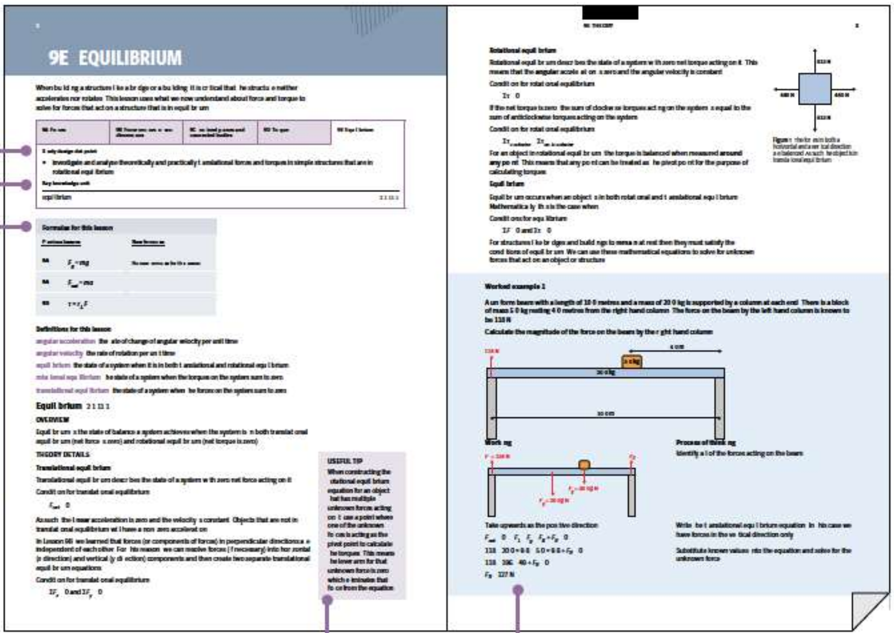
FEATURES OF THIS BOOK

Edrolo's VCE Physics Units 1 & 2 textbook has the following features.

Study design dot points from the VCAA curriculum provide explicit links between our lessons and the syllabus.

Key knowledge units break down the theory into smaller chunks and can be used to help navigate the corresponding theory lesson videos online.

Formulas for this lesson show any formulas that were introduced in earlier lessons, along with the lesson identification, and any formulas that will be introduced throughout the lesson.

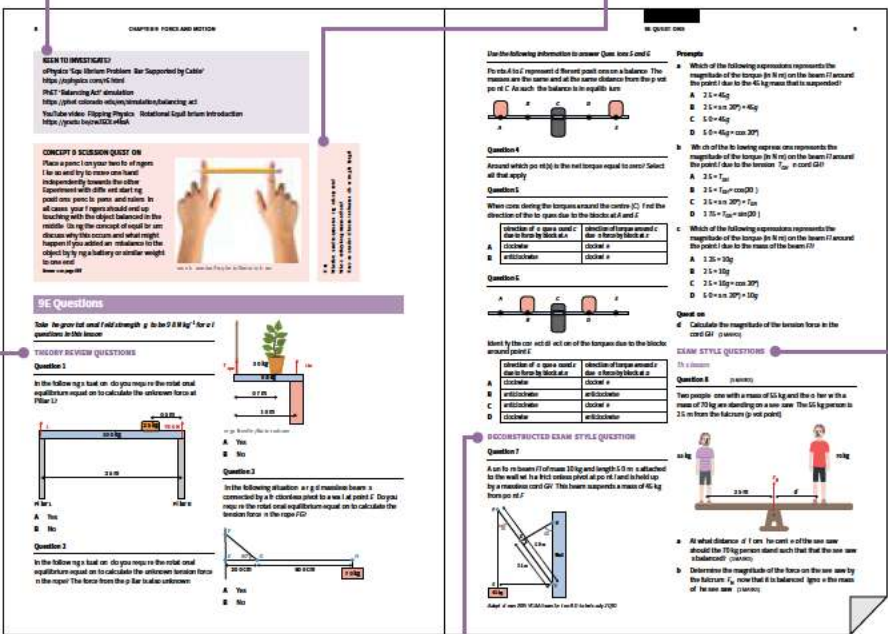


Useful tips address common misconceptions.

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

Keen to investigate boxes provide suggested links for students to explore physics concepts using simulations, videos, or other online material to both consolidate and deepen their understanding beyond the study design.

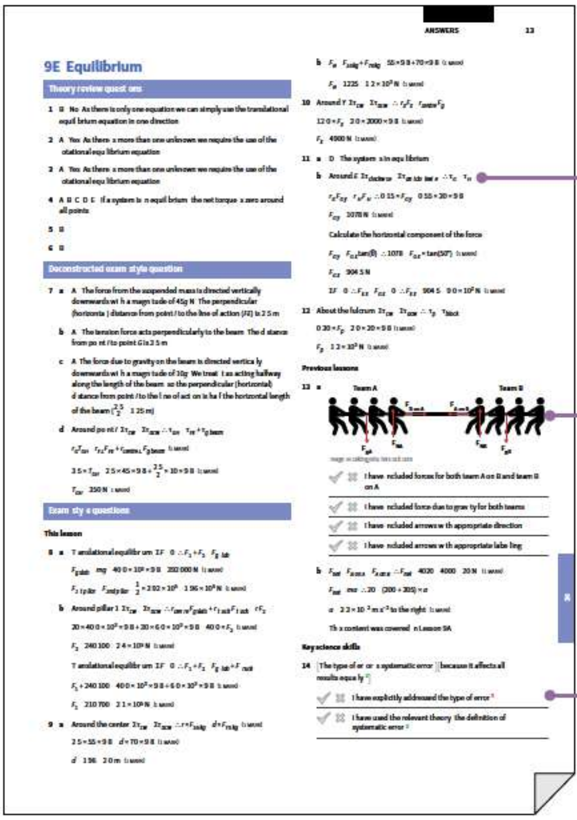
Concept discussion questions encourage students to discuss relatable situations where the physics concepts from the theory apply. They are designed to be accessible to all students while promoting a deeper understanding.



Exam-style questions reflect the style of your end-of-year exam in Year 12. These include questions from within the lesson, from previous lessons, and testing key science skills in the context of the theory you just learned.

Theory review questions test if students can remember the basic theory and overcome common misconceptions. They are stepping stones between the content and exam-style questions.

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

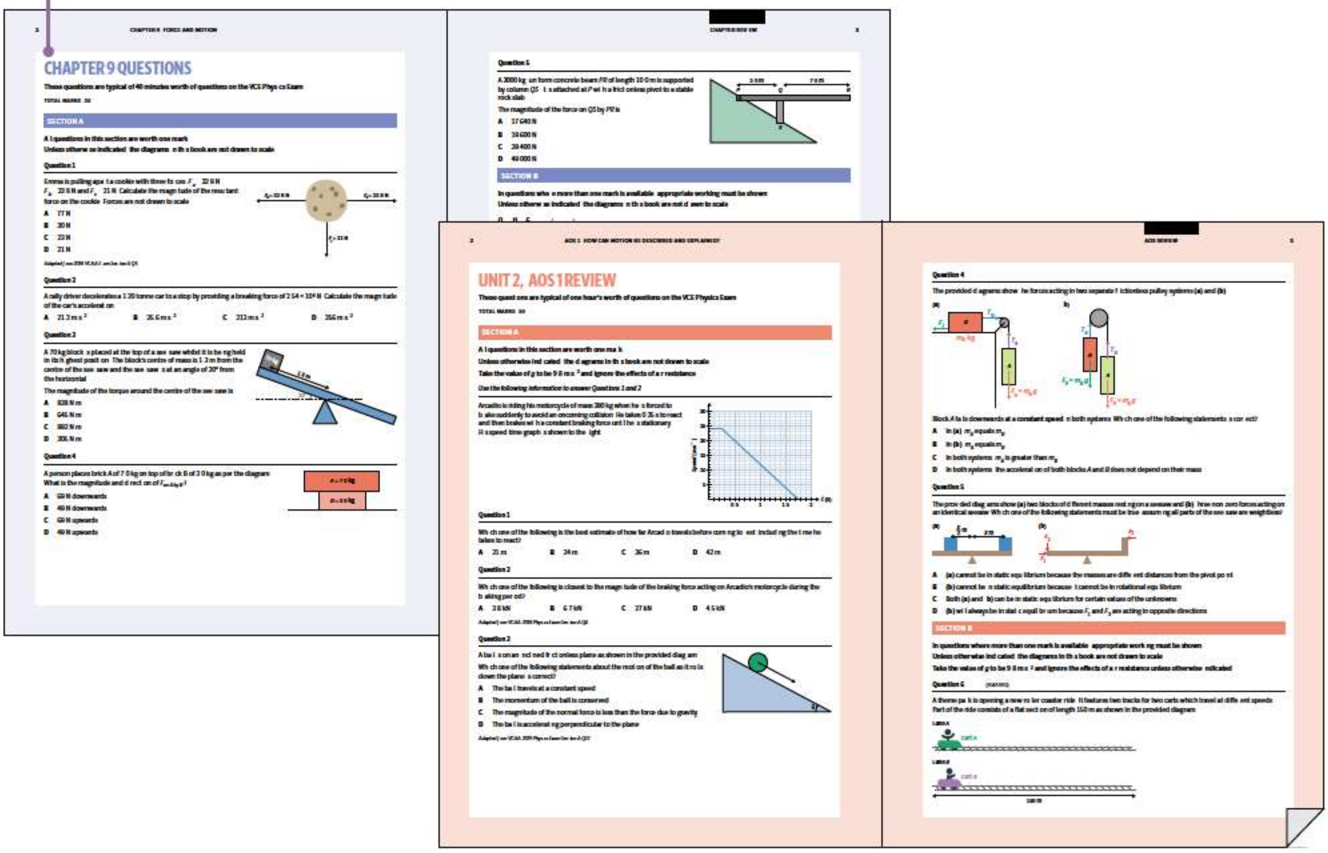


Calculation responses show full working along with mark allocations to help students form good habits and to provide more detailed guidance for students.

Worded responses and visual responses include an exemplar answer, to show students what a full mark response looks like, as well as a checklist.

Checklists are provided for all worded responses and visual responses. They explain the purpose of each part of a full-mark answer to help students develop their scientific communication skills.

The **chapter** and **area of study reviews** consist of exam-style questions that cover the content from that chapter or area of study. They are structured like the end-of-year exam in Year 12, consisting of a Section A with multiple choice questions and a Section B with short answer questions.



Practical investigations

01

This chapter will introduce and develop the key science skills, which are applicable to all practical, research, and investigation tasks throughout Units 1–4. In particular, these skills will build the foundation of knowledge that you will use to conduct the practical investigation for Unit 2 AOS 3. To do this, we will examine the key knowledge dot points related to Unit 2 AOS 3 in combination with the key science skills outlined in the study design.

Key knowledge

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (thermodynamics, construction of electric circuits, mechanics), and/or the evaluation of a device; precision, accuracy, reliability and validity of data; and identification of uncertainty
- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies
- observations and experiments that are consistent with, or challenge, current physics models or theories
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the conventions of scientific report writing including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references.

The development of a set of key science skills is a core component of the study of VCE Physics and applies across Units 1 to 4 in all areas of study. In designing teaching and learning programs and in assessing student learning for each unit, teachers should ensure that students are given the opportunity to develop, use and demonstrate these skills in a variety of contexts when undertaking their own investigations and when evaluating the research of others. As the complexity of key knowledge increases from Units 1 to 4 and as opportunities are provided to undertake investigations, students should aim to demonstrate the key science skills at a progressively higher level.

Key science skills

- Develop aims and questions, formulate hypotheses and make predictions
- Plan and undertake investigations
- Comply with safety and ethical guidelines
- Conduct investigations to collect and record data
- Analyse and evaluate data, methods and scientific models
- Draw evidence-based conclusions
- Communicate and explain scientific ideas

1A ASKING QUESTIONS, IDENTIFYING VARIABLES, AND MAKING PREDICTIONS

'Why' is a great question to ask. Why is the sky blue? Why do things fall? Why do dark objects that have been left in sunlight become hotter than light objects?

Science is the process of asking questions and seeking explanations for how the universe behaves so that we can make informed and accurate predictions. Physics is the part of science that focuses on the most fundamental features of the universe: matter and energy. This lesson will explain the scientific method as a process of seeking answers to questions by testing predictions involving different variables.

1A Asking questions, identifying variables, and making predictions	1B Scientific conventions	1C Collecting data	1D Representing and analysing data	1E Gradients of lines of best fit

Study design dot points

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (thermodynamics, construction of electric circuits, mechanics), and/or the evaluation of a device; precision, accuracy, reliability and validity of data; and identification of uncertainty
- observations and experiments that are consistent with, or challenge, current physics models or theories

Key science skills dot points

- determine aims, hypotheses, questions and predictions that can be tested
- identify independent, dependent and controlled variables
- systematically generate, collect, record and summarise both qualitative and quantitative data
- explain how models are used to organise and understand observed phenomena and concepts related to physics, identifying limitations of the models

Key knowledge units

The scientific method	2.3.2.1
Variables and types of data	2.3.2.2
Theories and models	2.3.5.1

No previous or new formulas for this lesson

Definitions for this lesson

controlled variable a variable that has been held constant in an experiment in order to test the relationship between the independent and dependent variables

dependent variable a variable that the experimenter measures, which is predicted to be affected by the independent variable. Dependent variables are plotted on the vertical axis of graphs

hypothesis a proposed explanation that predicts a relationship between variables and can be tested through experimentation

independent variable the variable that the experimenter manipulates (selects or changes), which is predicted to have an effect on the dependent variable. Independent variables are plotted on the horizontal axis of graphs

model (scientific) a representation of a physical process that cannot be directly experienced

observation the acquisition of data using senses such as seeing and hearing or with scientific instruments

qualitative data data that cannot be described by numerical values

quantitative data data that can be described by numerical values

theory (scientific) an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation

The scientific method 2.3.2.1

OVERVIEW

The scientific method is a way of reasoning. It is a process of collecting and analysing information to disprove incorrect explanations about the world. This process provides great confidence in explanations about the world which have not been disproved.

THEORY DETAILS

The scientific method is a process which begins with the idea that all possible explanations for an observation could be true **unless (and until) they are disproved**. The process then follows a sequence of logical steps to gather information in order to test an explanation, known as the 'hypothesis'. That is, we try to disprove the hypothesis. If, after multiple rigorous attempts to do this, the hypothesis has not been disproved then we have greater confidence that it is a correct explanation for our observations. This determination to disprove our own explanations is what makes scientific conclusions so powerful.

This section outlines the general process of following the scientific method, along with descriptions of its application to an example experiment for each step (in the right-hand column).

Step 1: Observe and question

We observe a physical phenomenon and ask 'why does this happen?' Sometimes we need to break the question into more specific parts such as 'what are the factors that affect…?' When we have answered this question, we could move to the question of **why** the identified factors have the effect that they do.	For example, we put a large jug of water and a small jug of water into the same freezer, and we observe that the water in the larger jug takes longer to freeze than the water in the smaller jug. We ask 'what are the factors that affect how long it takes to freeze water?'

Step 2: Formulate a hypothesis

A hypothesis should make a testable prediction by describing the effect of changing one variable on another variable. To ensure the hypothesis meets this requirement, it can help to follow a structure such as: • If [describe predicted physics principles] then [describe the predicted change to the dependent variable] when [the independent variable] is increased. • It is predicted that [increasing/decreasing][independent variable] will [increase/decrease][dependent variable] because [describe predicted relationship between independent variable and dependent variable].	We consider which conditions were (or could have been) different between the two jugs. • The larger jug had a greater total surface area of water. • The larger jug had a greater volume of water. • The jugs **might** have had different initial temperatures. • The jugs **might** have been made from different materials. We decide that the different surface area might be the best explanation for the different freezing times. So we formulate a hypothesis: 'If the time taken for water to freeze is directly related to its total surface area, then the time taken for a fixed volume of water to freeze will increase when its surface area increases.'

Step 3: Experiment (test the hypothesis)

In performing an experiment, only an independent variable should be deliberately changed. The dependent variable should then be measured. All other variables (controlled variables) should be kept constant. We record our method in detail so that another experimenter could attempt to replicate it in order to verify our results. Lesson 1C will further explain this section of the scientific method.	We measure the time it takes to freeze water in a variety of different shapes that have different surface areas but we try to keep all of the following conditions constant: water volume (250 cm^3), initial water temperature (20°C), freezer temperature (–18°C), and container material (silicone). We use nine different values of surface area. Using a greater number of different values of the surface area will give us greater confidence in any trends we observe. We take five measurements of the freezing time for each value of the surface area and then calculate the average time for each. The example results are shown in Table 1.

Table 1 Example results for the time taken for water to freeze with different surface areas

Surface area (cm^2)	Time to freeze (minutes)					
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
200	299	287	295	297	307	**297**
300	254	268	260	274	264	**264**
400	230	244	224	240	232	**234**
500	197	207	213	201	217	**207**
600	170	188	190	170	182	**180**
700	169	157	161	159	149	**159**
800	148	128	136	140	138	**138**
900	113	115	127	123	107	**117**
1000	87	103	91	97	107	**97**

Step 4: Analyse and conclude

We should present information in a way that makes it clear what (if any) relationship exists between the variables in our experiment. Plotting graphs of the dependent variable versus the independent variable is a useful visual way of identifying relationships.

We try to make conclusions based on the analysis as to whether the data supports the hypothesis.

We acknowledge any factors that may have affected our results which we could not control or any uncertainty in our results.

We can never have complete certainty that the conclusion is true because there may be variables which we did not correctly control or even recognise.

Lessons 1D and 1E will further explain this section of the scientific method.

We choose to represent the data on a graph (see Figure 1), with the surface area on the horizontal axis and the average time to freeze on the vertical axis.

We notice that the time for the water to freeze seems to **decrease** as surface area increases.

We conclude that our results **do not support our hypothesis** that 'increasing the surface area of water will increase the time it takes to freeze'.

Even though we kept the volume constant, there may have been other differences in the geometry for each value of the surface area such as the existence/angles of corners.

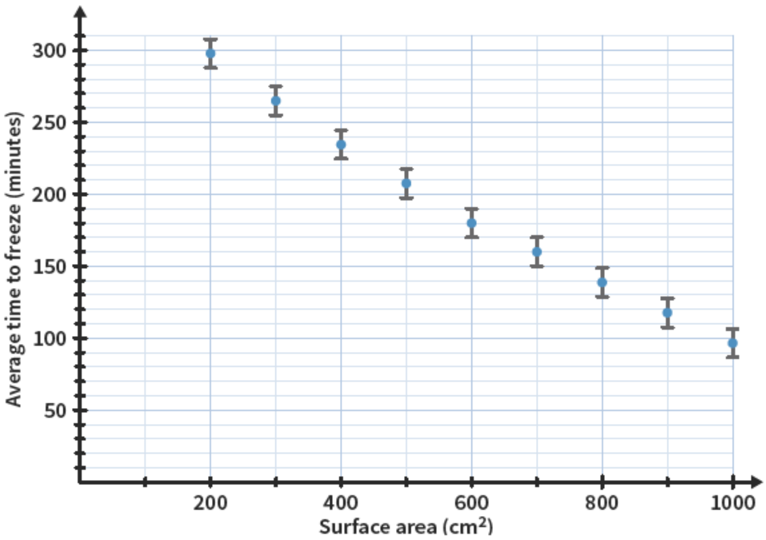


Figure 1 A graphical representation, including uncertainty bars, of the data from Table 1. Uncertainty bars will be covered in Lesson 1D.

Step 5: Share the results

We make our results (and the method we used) public for other experimenters to view.

If other experimenters conduct their own experiments freezing water and find similar results, then we become increasingly confident that increasing surface area decreases the time taken for water to freeze.

Variables and types of data 2.3.2.2

OVERVIEW

An independent variable is a variable that the experimenter directly and intentionally changes. A dependent variable is a variable that the experimenter measures. A controlled variable is a variable which is kept constant. Variables can be described by a numerical value (quantitative) or described by non-numerical characteristics (qualitative).

THEORY DETAILS

In order to conduct a valid experiment according to the scientific method, we need to investigate the relationship between variables: what happens to variable *Y* when we change variable *X*? To have confidence in the relationship between variables, we need to make sure that any other conditions which might affect the results are kept constant.

- An independent variable is a variable that the experimenter directly and intentionally changes (to have particular chosen values) in order to determine what (if any) effect it has on the dependent variable. For the results of an experiment to be valid, we should change only one independent variable at a time.
- A dependent variable is a variable that the experimenter measures in order to determine whether it is affected by (dependent on) the independent variable.
- A controlled variable is a variable which is kept constant to avoid potentially affecting the results for the dependent variable.

Table 2 Classification of the variables used in the example experiment which was described in the context of the scientific method

Variable classification	Example(s)
Independent variable	Surface area of water/ice
Dependent variable	Time taken to freeze
Controlled variable	Volume of water Initial temperature of water Temperature of freezer Container material

Quantitative data

Quantitative data describes any data which can be easily described with numerical values. Surface area, time, volume, and temperature are all properties which should be described by quantitative data.

Qualitative data

Qualitative data describes any data which cannot be (easily) described with numerical values. The material from which a container is made may be more easily described by non-numerical data (such as silicone) and so it would typically be considered qualitative data. If we wanted to describe the material in greater detail then we would use quantitative data: the relevant physical properties of the material (such as thermal conductivity and density) are all best described with quantitative data. Note that assigning numbers to data that would otherwise be qualitative (e.g. assigning numbers to tennis ball brands) does not make it quantitative.

Theories and models 2.3.5.1

OVERVIEW

In science, a theory is an explanation which is widely accepted to be true due to consistent and repeated observations which support the explanation. Models are often used in science to help explain a theory by building on concepts which we already understand.

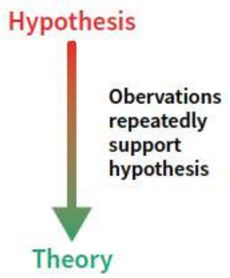


Figure 2 The progression of a possible explanation from a hypothesis to a theory

THEORY DETAILS

When the predictions made by a hypothesis have been tested many times, and the results consistently support the hypothesis, then the scientific community will consider the hypothesis to be true with a high degree of confidence. At this point, the explanation is now considered a scientific theory.

Remember that in science we can never say something is correct with complete certainty. Any explanation must be considered possible until it has been disproved (although scientists will favour the explanation with the least assumptions). An example of this is the explanation of gravity. Issac Newton developed a universal law of gravitation, which was considered to be a correct theory for over 200 years. However, in very particular situations it made predictions that did not align with observations. Albert Einstein developed an alternative explanation which has been shown to make correct predictions even in the situations where Newton's explanation fails. Einstein's explanation is the theory of general relativity.

Models simplify concepts for us to understand more easily when the concepts cannot be directly experienced or observed, especially when the details of the concept are complex. In general, all models have limitations and it is important to understand what they are. For example, we usually model matter as being continuous because this is consistent with what we see and feel. This model is useful for most applications relevant to our lives. However, our understanding of atomic theory tells us that matter consists of atoms, which are discrete and the mass of each atom is concentrated at the nucleus with mostly empty space around it. This reality is important if we are dealing with physics at very small scales when we should no longer model matter as being continuous.

Examples of models we use in VCE Physics are the particle model of atomic nuclei, the electromagnetic wave model for light, and a vector model for forces.

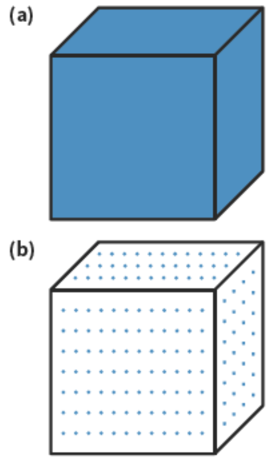


Figure 3 **(a)** Our brains model solid objects as continuous matter but **(b)** if we draw the locations of where the matter is concentrated, we see the object is mostly empty space. This diagram is not to scale.

Theory summary

- The scientific method is a way of reasoning in order to create correct theories about how the world works by testing whether or not a hypothesis is supported by observations.
- A hypothesis is a proposed explanation which makes testable predictions about the relationship between variables.
- An independent variable is directly changed by the experimenter.
- A dependent variable is observed or measured by the experimenter.
- A controlled variable is kept constant to avoid affecting the observations or measurements of the dependent variable.
- A scientific theory is a widely accepted explanation – it is the progression of an explanation from a hypothesis that has been confirmed with high confidence.
- Scientific models are representations which help explain physical theories.

KEEN TO INVESTIGATE?

YouTube video: Matthew Rath – Neil Degrasse Tyson Analogy for the Scientific Method
youtu.be/6FvSXI2iBcA

YouTube video: Seabala – Feynman on Scientific Method
youtu.be/EYPapE-3FRw

YouTube video: Sprouts – The Scientific Method: Steps, Examples, Tips, and Exercise
youtu.be/yi0hwFDQTSQ

1A Questions

THEORY REVIEW QUESTIONS

Question 1

A hypothesis should always

A predict the relationship between variables in an experiment.

B predict the specific values that will be measured in an experiment.

Question 2

Which of the following statements about the scientific method are true? *(Select all that apply)*

I The scientific method guarantees that correct conclusions will be obtained.

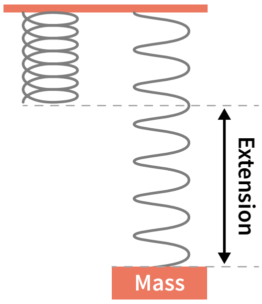
II The scientific method attempts to systematically eliminate incorrect explanations about the world.

III The more data collected and the more independent experiments conducted, the greater the confidence we can have in the conclusions of experiments that follow the scientific method.

IV We have confidence in a hypothesis that is supported by the scientific method because the experimenter has tried without success to disprove the hypothesis.

Question 3

A student conducts an experiment in which she attaches different masses to a hanging spring and measures the extension of the spring for each mass. She uses the same spring for all measurements. Match the type of variable with the variable in this experiment.



Type of variable

- Independent variable
- Dependent variable
- Controlled variable

Variable in this experiment

a Extension of spring

b Spring used

c Mass attached

Question 4

Categorise measurements of the following experimental variables as either **quantitative data** or **qualitative data**.

I The length of a ramp down which a ball rolls

II The type of ball (basketball, soccer ball etc.)

III The material from which the ball is made

IV The angle of the ramp

V The diameter of the ball

Question 5

For each statement, choose the type of explanation/ representation that it is best described by.

Explanation/representation

- Scientific theory
- Scientific model
- Scientific hypothesis

Statement

a The shape of the Earth is treated as a perfect sphere for the purpose of calculations.

b Ice melts into water when provided with sufficient heat.

c If larger mass objects roll downhill at a greater rate than smaller mass objects, then the time taken for the cart to reach the bottom should decrease when the mass on the cart is increased.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (5 MARKS)

Esther conducts an experiment in which she measures the maximum distance from her phone that she can hear the message alert tone for various volume settings (identified as 'quiet', 'medium', 'loud', and 'very loud') on the phone. She uses the same message alert tone for each trial and conducts the experiment in a large quiet outdoor space.

a Identify the independent variable and whether it is measured with quantitative data or qualitative data. (2 MARKS)

b Identify the dependent variable and whether it is measured with quantitative data or qualitative data. (2 MARKS)

c Identify a controlled variable in this experiment. (1 MARK)

Adapted from 2017 VCAA Exam Section B Q9b

Question 7 (1 MARK)

A simple representation that helps to describe and predict scientific results but which is known to be incomplete or partly incorrect is best described as

A a hypothesis.

B a scientific model.

C a scientific theory.

D an observation or measurement.

Question 8 (1 MARK)

A logical prediction based on existing facts or observations is best described as

A a hypothesis.

B a scientific model.

C a scientific theory.

D an observation or measurement.

Question 9 (1 MARK)

A conclusion that is formed with high confidence due to withstanding rigorous testing and which can explain observations and predict the results of future experiments is best described as

A a hypothesis.

B a scientific model.

C a scientific theory.

D an observation or measurement.

1B SCIENTIFIC CONVENTIONS

Scientific conventions such as SI units and the correct treatment of significant figures in physics let us efficiently convey information, not only about the values we measure, but also about the precision of those values.

1A Asking questions, identifying variables, and making predictions	1B Scientific conventions	1C Collecting data	1D Representing and analysing data	1E Gradients of lines of best fit

Study design dot point

- the conventions of scientific report writing including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references

Key science skills dot point

- process quantitative data using appropriate mathematical relationships, units and number of significant figures

Key knowledge units

Units of measurement	2.3.8.1
Significant figures	2.3.8.2

No previous or new formulas for this lesson

Definitions for this lesson

magnitude the size or numerical value of a quantity without sign (positive or negative) or direction

SI unit the accepted standard unit used for measuring a quantity. It is an abbreviation of "le Système international d'unités"

significant figures all digits quoted starting with the first non-zero digit giving an indication of the confidence in a measurement

Units of measurement 2.3.8.1

OVERVIEW

The SI system of measurement is used globally as the preferred system of measurement for scientific contexts. It comprises the SI units – the units the scientific community has decided to use to express physical quantities.

THEORY DETAILS

We use units of measurement as a standard reference for the magnitude of different quantities so that different physical objects and processes can be compared. There are many different systems of measurement used in different countries and contexts. Examples include the International Nautical system (fathoms, nautical miles) and the imperial system (inch, foot, yard, mile).

The system of units used in scientific disciplines is the International System of Units (abbreviated to SI from the French name Système International). In most cases, the values used in physics formulas must be measured in SI units. This system comprises seven 'base' units which are defined in terms of physical constants or processes. For example, the metre is defined with reference to the speed of light, the second is defined by the frequency of energy transitions in caesium–133, and the kilogram (as of May 20, 2019) is defined by Planck's constant.

Image: AlexLMX/Shutterstock.com

Figure 1 A 3D rendering of the IPK (International Prototype of the Kilogram). The kilogram was the last unit to be defined in terms of a physical object. Prior to 2019, it was defined by the mass of the IPK, a cylinder made of platinum and iridium that was kept in a vault in France.

Table 1 The base SI units and their symbols

Quantity	Unit name	Symbol
Time	second	s
Length	metre	m
Mass	kilogram	kg
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

The candela and mole will not be used in VCE Physics.

All other SI units are derived from the base SI units. That is, they are formed by multiplying or dividing the SI units. They are appropriately called 'derived SI units'.

Table 2 The derived SI units and their symbols. The equivalent base SI units in this table are not required knowledge for VCE Physics.

Quantity	Unit name	Symbol	Equivalent base SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg\ m\ s^{-2}$
Energy	joule	J	$kg\ m^2\ s^{-2}$
Power	watt	W	$kg\ m^2\ s^{-3}$
Electric charge	coulomb	C	A s
Voltage	volt	V	$kg\ m^2\ s^{-3}\ A^{-1}$
Resistance	ohm	Ω	$kg\ m^2\ s^{-3}\ A^{-2}$
Magnetic flux	weber	Wb	$kg\ m^2\ s^{-2}\ A^{-1}$
Magnetic flux density	tesla	T	$kg\ s^{-2}\ A^{-1}$

Certain quantities like velocity and acceleration do not have their own dedicated SI units. Instead they each use equivalent base (and/or derived) SI units. These units are required knowledge for VCE Physics.

Table 3 The equivalent base/derived SI units for other select quantities

Quantity	Equivalent base/derived SI units
Velocity	$m\ s^{-1}$
Acceleration	$m\ s^{-2}$
Area	m^2
Volume	m^3
Resistivity	Ω m
Specific heat capacity	$J\ K^{-1}\ kg^{-1}$
Specific latent heat	$J\ kg^{-1}$

When an answer is asked for in SI units, this encompasses both base units and derived units.

The order of magnitude of an SI unit can be adapted through prefixes. These indicate the factor by which the value should be multiplied. For example, one nanometre is 10^{-9} metres.

Table 4 The SI prefixes. This information is included in the VCE Physics exam formula sheet.

Symbol	p	n	μ	m	k	M	G
Prefix	pico	nano	micro	milli	kilo	mega	giga
Order of magnitude	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{3}	10^{6}	10^{9}

Examples:

$9.0\ pm = 9.0 \times 10^{-12}\ m$

$3\ Ms = 3 \times 10^{6}\ s$

$2.3 \times 10^{5}\ mJ = 2.3 \times 10^{2}\ J$

The SI unit for mass (the kilogram) is a special case since it has a prefix already within its name ('kilo'). Prefixes are put in front of 'grams' instead. For example, one milligram expressed in SI units would be 10^{-6} kilograms.

USEFUL TIP

We can gain a lot of clues about physics problems from unit analysis. For example, if we see the unit for velocity is m s^{-1} (metres divided by seconds), that indicates that the formula for velocity will contain some length variable divided by some time variable.

Similarly, if we forget the unit for frequency is hertz, but we remember that frequency is calculated as the reciprocal of the period $\left(f = \frac{1}{T}\right)$ where period is measured in seconds, we can determine that an equivalent unit for frequency is s^{-1}.

Significant figures 2.3.8.2

OVERVIEW

Significant figures are all the digits in a value that convey how well that value is confidently known. The number of significant figures in a value can be determined using a set of rules. Large and small numbers should be expressed in scientific notation so that they are written to an appropriate number of significant figures.

THEORY DETAILS

Significant figures indicate to what degree we know a value is correct. For example, if we have a number with two significant figures, that indicates to the reader that we are not confident in the value of that number past those first two digits. This ties heavily into the concept of uncertainty which will be explored in Lesson 1C.

There is a certain set of conventions taken in how we write numbers in VCE Physics so that the reader can understand how confident we are in our values.

- Leading zeros are never significant
- All non-zero digits are always significant
- Trailing zeros are always significant
- Zeros between digits are always significant

In summary, **all digits are significant except for leading zeros** in VCE Physics.

Scientific notation

We can use scientific notation to express large numbers to the correct amount of significant figures. We write numbers in scientific notation in the following form:

$$m \times 10^n$$

where m is a positive number greater than 1 and less than 10 (such as 5 or 4.56) and n is an integer (such as −6 or 17). All the digits in m should be significant, meaning there should be no leading zeros.

We use scientific notation for two reasons.

Firstly, it allows us to write very large and very small numbers with only a few digits (consider how we would write 6.67×10^{-11} without using scientific notation). This is especially important in physics, as we often work on quantum (very small) or astronomical (very large) scales.

Secondly, scientific notation allows us to write large numbers even if they have a small number of significant figures. For example, if we write a distance measurement as 2000 m (4 significant figures), it implies that the measurement is confidently known to the nearest metre. But if our measurement was taken to the nearest 100 m, then we should write the measurement as 2.0×10^3 m (2 significant figures).

USEFUL TIP

When converting from standard notation to scientific notation, the magnitude of n is the number of digits between the space after the first significant digit and the decimal place.

$n = 6$: 5600000 ⟷ 5.6×10^6

$n = -4$: 0.00043 ⟷ 4.3×10^{-4}

If the first significant digit is before the decimal place, move the decimal place n digits to the left. If the first significant digit is after the decimal place, move the decimal place n digits to the right (the n value is negative).

Table 5 Examples of how to write numbers using scientific notation

Number	Scientific notation	Significant figures	Number	Scientific notation	Significant figures
230	2.30×10^2	3	0450.2	4.502×10^2	4
0.00067	6.7×10^{-4}	2	0.3700	3.700×10^{-1}	4
5.034	5.034×10^0	4	7.00×10^{-6}	7.00×10^{-6}	3
2×10^{-6}	2×10^{-6}	1	37	3.7×10^1	2

Significant figures in calculations

- When two values are being added or subtracted, the number of decimal places in the answer should match the value from the addition/subtraction with the fewest decimal places
- When two values are being multiplied or divided, the number of significant figures in the answer should match the value from the multiplication/division with the fewest significant figures

These rules allow the results of our calculations to express the correct level of confidence given the level of certainty in the numbers with which we started.

Examples:

$5 + 5 = 10$ (final answer has 0 decimal places as 5 has 0 decimal places)

$7 \times 4 = 3 \times 10^1$ (final answer has 1 significant figure as 7 and 4 both have 1 significant figure)

$34.477 + 2.31 = 36.79$ (final answer has 2 decimal places as 2.31 has 2 decimal places)

$34.477 \times 2.31 = 79.6$ (final answer has 3 significant figures as 2.31 has 3 significant figures)

USEFUL TIP

Calculations should be rounded to the correct amount of significant figures only in the last step. Otherwise, rounding during working can result in an incorrect answer.

The digits 0–4 round down, and 5–9 round up.

USEFUL TIP

The significant figures given for constants in the VCE Physics formula sheet limit the amount of significant figures in exam questions. For example, any question involving $c = 3.0 \times 10^8$ m s^{-1} will be limited to 2 significant figures.

Note: in worked answers in this book, we will provide additional significant figures in each line of working as it is good practice to do so to ensure accuracy in the final answer and it will make it easier for you to check your working. We will give the answer to the correct number of significant figures.

Theory summary

- SI units are used in scientific contexts, and most physical formulas require SI units to be used to attain correct values.
  - Prefixes can be added to SI units to indicate different orders of magnitude.
- Significant figure rule:
  - All digits are significant except leading zeros in VCE Physics.
- Numbers can be written in scientific notation by writing in the form $m \times 10^n$.

1B Questions

THEORY REVIEW QUESTIONS

Question 1

Identify the number of significant figures in the following numbers.

a 570

b 0.0085076

c 00673.6

d 9

e 2.00067

f 8.73×10^7

g 0.7800

h 607.50

i 7.00×10^{-6}

Question 2

Write the following numbers in scientific notation.

a 0.12

b 6000 (accurate to 2 significant figures)

c 0.000000030

d 8 900 000 (accurate to 2 significant figures)

e 0.00078

f 63 700 (accurate to 3 significant figures)

Question 3

Compute the following mathematical results using correct significant figure conventions. You are not required to give your answers in scientific notation.

a 6 + 38

b 37.564 − 4.2384

c 80 − 6.8

d 37.6 + 21.4

e 874.4 + 0.65

f 59.95 + 0.072

Question 4

Compute the following mathematical results following correct significant figure conventions. Give your answers in scientific notation.

a 649 × 14

b 4.6 × 7.24

c 7.38 ÷ 200

d $(4.76 \times 10^6) \times 5.2$

e 0561 × 58.34

f 20 ÷ 0.004

Question 5

Express the following quantities in terms of SI units and in scientific notation.

a 600 ms

b 6.4 kJ

c 0.400 µg

d 23 MΩ

e 360 nm

f 7.0 pA

Question 6

Select which of the following are SI units. (*Select all that apply*)

I seconds

II fahrenheit

III miles

IV ohms

V metres cubed (m^3)

VI grams

VII light-years

VIII metres

IX years

X hours

XI electron volts

XII litres

XIII volts

EXAM-STYLE QUESTIONS

This lesson

Question 7 (2 MARKS)

Calculate the electric potential energy (E) of a 4.00 C charge (Q) after passing through a 6.00 V (V) laptop charger to the correct number of significant figures. The formula for electric potential energy is $E = VQ$.

Question 8 (3 MARKS)

Calculate the average speed for the journey of a runner who takes 67.0 seconds to run 0.135 kilometres up a hill and a further 63 metres along a footpath to the correct number of significant figures. Average speed is calculated using $speed = \frac{total\ distance}{time}$.

1C COLLECTING DATA

Can we know any measurement in physics with absolute certainty? What are the important elements of designing experiments?

The ability to properly conduct experiments and gather data is an essential part of science. In this lesson we will discuss important considerations when collecting data: error, uncertainty, accuracy, precision, reproducibility, and repeatability.

1A Asking questions, identifying variables, and making predictions	1B Scientific conventions	1C Collecting data	1D Representing and analysing data	1E Gradients of lines of best fit

Study design dot points

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (thermodynamics, construction of electric circuits, mechanics), and/or the evaluation of a device; precision, accuracy, reliability and validity of data; and identification of uncertainty
- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies

Key science skills dot points

- select and use equipment, materials and procedures appropriate to the investigation, taking into account potential sources of error and uncertainty
- take a qualitative approach when identifying and analysing experimental data with reference to accuracy, precision, reliability, validity, uncertainty and errors (random and systematic)
- explain the merit of replicating procedures and the effects of sample sizes to obtain reliable data

Key knowledge units

Error	2.3.4.1
Uncertainty	2.3.2.3 & 2.3.4.2
Precision and accuracy	2.3.2.4
Validity	2.3.2.5
Repeatability and reproducibility	2.3.2.6

No previous or new formulas for this lesson

Definitions for this lesson

accuracy a relative indicator of how well a measurement agrees with the 'true' value of a measurement

error the difference between a measured value and its 'true' value

human error see personal error

personal error mistakes in an experiment's execution or analysis caused by a lack of care that negatively impact or invalidate the conclusions of an experiment

precision a relative indicator of how closely different measurements of the same quantity agree with each other

random error the unpredictable variations in the measurement of quantities

reliability a qualitative description of how likely it is that another experimenter can perform an experiment and find the same results within a small range

repeatability the closeness of agreement of results when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same lab)

reproducibility the closeness of agreement of results when an experiment is repeated by a different experimenter under slightly different conditions (using their own equipment and lab)

systematic error a consistent, repeatable deviation in the measured results from the true values, often due to a problem with the experimental design or calibration of equipment

uncertainty the qualitative appraisal of how well an experiment measures what it is intended to measure

validity the quality of an experiment measuring what it intends to measure

Error 2.3.4.1

OVERVIEW

Error refers to the difference between a measured value and its 'true' value.

THEORY DETAILS

Personal error

Personal errors are mistakes in an experiment's execution or analysis caused by a lack of care that negatively impact or invalidate the conclusions of an experiment. Personal error can also be called human error. Examples of personal errors include:

- Misreading the scale on a thermometer
- Measuring the voltage across the wrong section of an electric circuit
- Using the diameter instead of the radius when calculating the area of a circle

Data that has been impacted by personal error should be discounted.

Systematic error

Systematic errors are errors that uniformly affect the accuracy of data in an experiment. An uncalibrated weighing scale is an example of a cause of systematic error since each measurement would differ from the true value by a consistent amount. Parallax error, which occurs when an analogue scale is read at an angle to the display, is another cause of systematic error.

On a graph that is supposed to have a trend pass through the origin, having a non-zero *y*-intercept is usually an indicator of systematic error. This can be seen in Figure 1.

The effect of systematic errors **cannot** be improved by taking the average of multiple measurements because all the measurements will consistently be affected in the same way. The cause of any systematic error that is identified should be fixed and the experiment repeated. Possible sources of systematic errors that cannot be removed, or were not identified during the experiment, should be analysed in the discussion section of an experimental report when they are present.

Random error

Random error is the unpredictable variation in the measurement of quantities. In general, random errors can be reduced but not entirely avoided.

Any physical measurement will have an associated random error which is caused by uncontrolled variations in the conditions of an experiment between each trial. Try and measure the time it takes to drop a ball from a fixed height three times and you will find a slightly different result each time!

Random errors commonly originate from readings that are between the intervals of a measuring device or from taking a measurement when the values on a measuring device are fluctuating.

Random errors affect the precision and accuracy of measurements. Random errors can be reduced by choosing equipment and methods that will result in less variation, such as using a timer that is activated by an automatic sensor rather than a person timing with a stopwatch. The **effect** of random errors can be reduced by using an averaged result from repeated measurements.

The effect of random errors can be seen on a graph by data points sitting above and below their trendline, as seen in Figure 1.

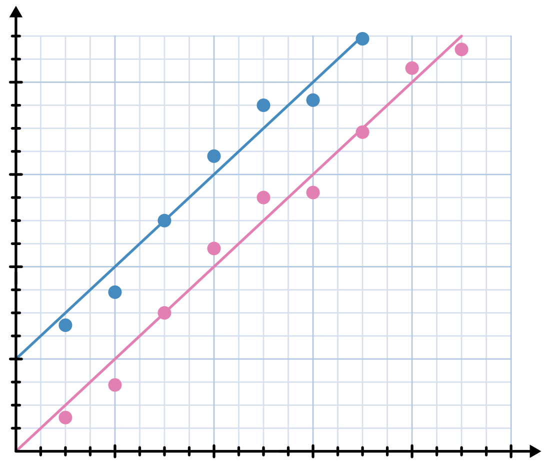


Figure 1 Plots of two experiments measuring a relationship between the same two variables. The 'true' relationship is linear and passes through the origin. The measurements plotted in blue have been affected by systematic error since all measurements are consistently above the 'true' values. All measurements have been affected by random error.

Uncertainty 2.3.2.3 & 2.3.4.2

OVERVIEW

Uncertainty is an indicator of a range that the 'true' value of a measurement should lie within.

THEORY DETAILS

Uncertainty

Uncertainty is an unavoidable part of experimentation and taking measurements. This means that there is always a level of doubt in the accuracy of a measured value. Uncertainty is not a "bad" thing. In fact, it is incredibly important to be honest with the level of uncertainty in scientific measurements so that there can be an appropriate level of confidence in the conclusions of an experiment.

Having uncertainty in measurements is unavoidable due to how measurements vary when repeated (random error). In fact, uncertainty can be thought of as an estimate of the maximum random error associated with a measurement. By using equipment with smaller intervals – such as a ruler with millimetre markings rather than centimetre markings – the level of uncertainty in an experiment can be reduced, but not eliminated.

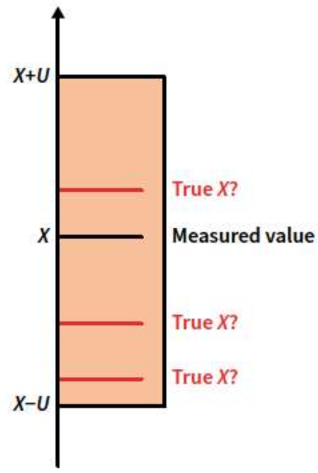


Figure 2 A quantity is measured to be $X \pm U$. This indicates the 'true' value of a measured quantity X should lie within the range of uncertainty U around X. It should not be assumed that the measured value X is the 'true' value.

Uncertainty can be expressed as an absolute uncertainty (in the same units as the measurement) or as a percentage of the measurement. For example, a measurement of 5.0 cm with an uncertainty of 0.2 cm can be written as:

- 5.0 ± 0.2 cm (absolute uncertainty); or
- 5.0 cm ±4% (relative/percentage uncertainty).

Absolute uncertainties should be expressed to one significant figure, and the measured value should be quoted to the place value of the uncertainty. Place value refers to the 'tens' place, 'ones' place, 'tenths' place. For example, if a measurement of 600 m is taken with a measured uncertainty of 10 m, the measurement should be written as $6.0 \times 10^2 \pm 0.1 \times 10^2$ m.

Uncertainty in an individual measurement due to a measuring device

The uncertainty in the value measured by a measuring device is half of the smallest increment on the measuring device. For example, on a digital scale that gives values to the nearest 0.01 kg, the uncertainty is ±0.005 kg. If a metrestick has measurement intervals of 0.001 m, the uncertainty is ±0.0005 m. The measured value should have the same lowest place value as the uncertainty. For example, using the ruler shown in Figure 3, the side of the box should be recorded as 5.40 ± 0.05 cm.

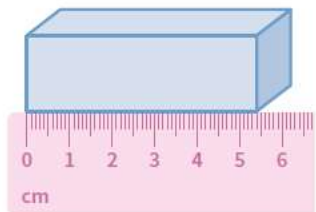


Figure 3 A box being measured by a ruler. The smallest increment on the ruler is 0.1 cm.

Uncertainty in the average of multiple measurements

As measurements will vary each time they are recorded due to the effects of random errors, measurements should be repeated multiple times and averaged in order to find a more accurate estimate of the 'true' measurement.

The uncertainty of multiple measurements depends on how much difference there is in the measured values. In VCE Physics, when calculating the uncertainty in the average of multiple measurements, the uncertainty can be taken as the magnitude of the difference between the average value of the measurements and the most extreme measurement (the individual measurement which is furthest from the average).

Worked example 1

Calculate the average net force and associated uncertainty of a ball being kicked by a student based on the force data in the table.

Trial	1	2	3	4	5
Net force (N)	20.0 ± 0.1	20.6 ± 0.1	19.8 ± 0.1	18.2 ± 0.1	20.4 ± 0.1

Working

Average net force $= \dfrac{20.0+20.6+19.8+18.2+20.4}{5} = 19.8$ N

Uncertainty: $|19.8 - 18.2| = 1.6$ N ≈ 2 N

Therefore, average net force is

20 ± 2 N

Process of thinking

The average net force is given by the addition of each net force divided by the number of trials.

The uncertainty is given as the difference between the average net force and the most extreme value.

Note that we round 1.6 up to 2 because the uncertainty should be given to one significant figure.

When there is uncertainty in an average value due to multiple measurements **and** an uncertainty in individual measurements due to the measuring device, we should always take the larger value of uncertainty.

Worked example 2

Calculate the average net force and associated uncertainty of a ball hitting a wall based on the force data in the table.

Trial	1	2	3	4	5
Net force (N)	20.0 ± 0.5	20.0 ± 0.5	20.0 ± 0.5	20.5 ± 0.5	20.5 ± 0.5

Working

Average net force = $\frac{20.0+20.0+20.0+20.5+20.5}{5}$ = 20.2 N

Uncertainty: |20.5 − 20.2| = 0.3 N

Therefore, average net force is

20.2 ± 0.5 N

Process of thinking

The average net force is given by the addition of each net force divided by the number of trials.

The uncertainty is given as the difference between the average net force and the most extreme value.

Note that the uncertainty of an individual value (0.5 N) is larger than the uncertainty in the average.

Precision and accuracy 2.3.2.4

OVERVIEW

Precision and accuracy are very specific concepts in physics. Precision describes how closely different measurements of the same quantity agree with each other. Accuracy describes how well the set of measurements relates to the 'true' value. They are both relative measures.

THEORY DETAILS

Precision is an indicator of how well a set of measurements agree with each other. It can be thought of as a measure of the spread or range of data – a bigger range is less precise. It is a relative indicator. A set of measurements cannot be 'precise', it can only be more or less precise than another set of measurements.

The precision of a set of measurements can be improved by having good experimental technique and using measuring devices with smaller uncertainties. Note that these are methods for reducing the size of random errors. In this sense, **precision is closely related to random error**.

USEFUL TIP

When asked to identify the more precise set of measurements, identify the set with the smallest range (maximum value – minimum value).

Accuracy is an indicator of how well a measurement agrees with the 'true' value of a measurement. This 'true' value is the value that would be measured if it were possible to take measurements with no errors. Like precision, a measurement cannot be objectively 'accurate', it can only be more or less accurate than another measurement.

The accuracy of a measurement can be improved by reducing systematic errors in the experimental design and choosing equipment and methods that will result in less random error. In this sense, **accuracy is related to both systematic errors and random errors.**

Accuracy can also be applied to sets of measurements. If the average of a set of measurements is closer to the 'true' value than the average of another set of measurements, then it is more accurate than that other set.

The effect of random error on the **accuracy of a set of measurements** can be reduced by increasing the number of measurements since the variations from the 'true' value of individual measurements will tend to offset each other when an average is taken from a large enough set. In this sense, taking multiple measurements can reduce the **effect** of random error (but it does not reduce the random error itself).

USEFUL TIP

When asked to identify the more accurate set of measurements, identify the set with an average that is closer to the 'true' value.

Validity 2.3.2.5

OVERVIEW

Validity in an experiment refers to whether an experiment actually measures what it intends to measure. The validity of an experiment depends on the experimental design, how the experiment is conducted, and how the results are processed and analysed.

THEORY DETAILS

An experiment is valid if it is able to successfully measure what it aims to measure. The validity of an experiment can be impacted before, during, and after performing an experiment.

Table 1 Some requirements for an experiment to be valid before, during, and after an experiment. This list is not exhaustive.

Time period	Elements necessary to be valid
Before the experiment	• Experiment is designed so that there is only one independent variable. • Experiment is designed so that it can measure the dependent variable. • Experiment is designed to minimise systematic error and personal error. • Sample sizes are appropriately large enough (this is more relevant in psychological experiments). • All necessary assumptions for analysis (such as simplifications) are addressed in the design of the experiment.
During the experiment	• Observer bias is minimised. • No controlled variables are allowed to change. • All steps of the scientific method are followed. • The experiment measures the correct dependent variable. • Appropriate equipment is used. • No personal error impacting results.
After the experiment (data analysis)	• All data is processed correctly. • All data is included and explained. Data cannot be arbitrarily selected to produce the desired trend. • Any outliers are addressed in discussion and are included in the initial data. • Results are examined, and the possibility of other causal relationships are considered. Correlation between two variables is not automatically assumed to mean causation. • Experiment is able to be repeated and reproduced.

Repeatability and reproducibility 2.3.2.6

OVERVIEW

The reliability of an experiment is a qualitative description of how likely it is that another experimenter can perform an experiment and find the same results within a small range, and it is primarily tested through an experiment's repeatability and reproducibility.

THEORY DETAILS

In order for the results of an experiment to be deemed reliable enough to draw strong conclusions, the experiment must be repeatable and reproducible.

Repeatability refers to the closeness of agreement of results (the precision) when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same lab).

Reproducibility refers to the closeness of agreement of results (the precision) when an experiment is repeated by a different experimenter under slightly different conditions (using their own equipment and lab).

Reproducibility is especially important because comparing results with a different experimenter helps reveal bias, systematic errors, or experimental flaws that impact the validity of an experiment.

The vital nature of reproducibility to draw conclusions is why the publication of the experimental reports in peer-reviewed journals is a key part of physics research. The validity of the experiment is then assessed in the publication process and it provides the necessary information for other experimenters to reproduce the experiment.

Table 2 Conditions for repeatability versus reproducibility

	Repeatability	Reproducibility
Experimenter	Same	Different
Conditions (lab, equipment)	Same	Different

Theory summary

- There are three kinds of experimental errors:
  - Personal error: mistakes in an experiment's execution or analysis
  - Systematic error: a consistent, repeatable deviation in the measured result from the true values
  - Random error: the unpredictable variations in the measurement of quantities
- Uncertainty is an indicator of a range that the 'true' value of a measurement should lie within.
  - Uncertainty in a measuring device is half the smallest measuring increment.
  - Uncertainty in the average of multiple measurements can be taken as the magnitude of the difference between the most extreme measurement and the average value.
- Precision and accuracy are relative measures describing the spread of a set of measured values and how well the set of measurements relates to the 'true' value.
  - A more precise set of measurements will have a smaller range of measurements. Precision is related to random error.
  - A more accurate set of measurements will have an average of the set of measurements closer to the true value. Accuracy is related to both systematic error and random error.
- An experiment is valid if it is able to measure what it intends to measure.
- Repeatability and reproducibility are qualities that describe how well the results of a repeat of an experiment agree with the original experiment.

KEEN TO INVESTIGATE?

VCAA Measurement in science
vcaa.vic.edu.au/curriculum/vce/vce-study-designs/Physics/advice-for-teachers/Pages/MeasurementinScienceOverview.aspx

1C Questions

THEORY REVIEW QUESTION

Question 1

Which of the following statements are true?
(Select all that apply)

I Random error is caused by incorrectly reading the scale when following the experimental design.

II Controlled variables cannot be changed throughout a valid experiment.

III Data that is known to have been affected by personal error should be kept and treated to be as valid as all other data.

IV It is possible to know a value measured in an experiment with complete certainty.

V An experiment being repeatable increases the reliability of its conclusions.

VI Whether or not an experiment will be valid depends entirely on the planned experimental method.

VII Using more precise equipment can reduce random error.

VIII Systematic error consistently affects all data points.

IX Uncertainty is avoidable.

X The uncertainty in an individual measurement due to a measuring device is half the smallest increment on the measuring device.

XI A single set of measurements cannot be both accurate and precise.

XII Data that is far from the average (outliers) can be automatically excluded from a set of data.

EXAM-STYLE QUESTIONS

This lesson

Question 2 (1 MARK)

Error is **best** described as

A a quantitative estimate of the random error associated with the measurement.

B how confident a scientist feels while performing data analysis.

C the process of repeating a measurement to improve reliability.

D the difference between a measured value and its 'true' value.

Question 3 (1 MARK)

Which of the following statements regarding experimental uncertainty is false?

A Repeating measurements cannot eliminate uncertainty.

B Using more precise equipment can reduce the level of uncertainty.

C The 'true' value is the difference between the most extreme measurement and the average measurement.

D Random errors are considered when calculating uncertainty.

Question 4 (1 MARK)

When a measurement is taken from the average of multiple readings, taking more readings

A increases the effect of random error.

B does not change the effect of random error.

C reduces the effect of systematic error.

D does not change the effect of systematic error.

Question 5 (1 MARK)

Which of the following statements about error is correct?

A Random errors cause the measured value to be uniformly different from the true value.

B Personal errors are unavoidable.

C Systematic errors do not affect all data points.

D Random errors are unavoidable.

Question 6 (1 MARK)

Which of the following is true about reproducibility and repeatability?

A A repeatable experiment will have closely agreeing results when the experiment is repeated by a different experimenter using different equipment.

B An experiment being repeatable means that there is no experimenter bias.

C The reliability of an experiment depends on whether the experiment is reproducible and repeatable.

D The reproducibility of an experiment refers to the accuracy of results when an experiment is repeated by a different experimenter under slightly different conditions.

Question 7 (1 MARK)

Georgina and Belle measure the current through a specific circuit on separate occasions.

Georgina takes the following readings: 2.30 V, 3.10 V, 2.60 V, and 2.90 V (average 2.73 V).

Belle takes the following readings: 1.50 V, 2.70 V, 2.50 V, and 3.90 V (average 2.65 V).

The true value of the voltage is 2.60 V.

Which of the following statements best describes these sets of measurements?

A Both sets of measurements are equally precise.

B Georgina's measurements are more accurate than Belle's results.

C Both sets of measurements are equally accurate.

D Belle's measurements are less precise than Georgina's results.

Adapted from 2017 VCAA Exam Section A Q18

Question 8 (1 MARK)

Students set up an experiment to measure the value of Earth's gravitational field strength g. They take five measurements, as follows:

- 9.75 m s^{-2}
- 9.86 m s^{-2}
- 9.82 m s^{-2}
- 9.78 m s^{-2}
- 9.84 m s^{-2}

Systematic errors are negligible.

The most reasonable measurement uncertainty for the students to cite is

A 0.05 m s^{-2}.

B 0.06 m s^{-2}.

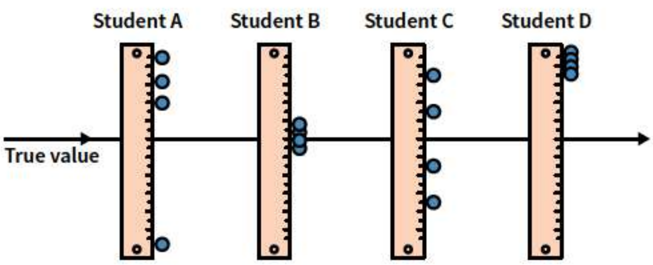
C 0.07 m s^{-2}.

D 0.005 m s^{-2}.

Adapted from 2017 VCAA Sample Exam Section A Q9

Use the following information to answer Questions 9–12.

Four students take a measurement of the length of a piece of wire. The measurements are then indicated as dots on a ruler (as shown on the diagram). The true value of the length of the wire is also indicated on the diagram.



Adapted from 2019 VCAA NHT Exam Section A Q20

Question 9 (1 MARK)

Which student's results are the most precise and accurate?

A Student A

B Student B

C Student C

D Student D

Question 10 (1 MARK)

Which student has results that are relatively precise but relatively inaccurate?

A Student A

B Student B

C Student C

D Student D

Question 11 (1 MARK)

Which student's results are the least accurate?

A Student A

B Student B

C Student C

D Student D

Question 12 (1 MARK)

Which student has results that are relatively accurate but relatively imprecise?

A Student A

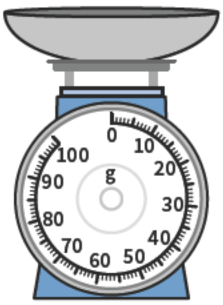
B Student B

C Student C

D Student D

Question 13 (1 MARK)

What is the best estimate for the uncertainty in this analogue weighing scale?



A 10 g

B 0.5 g

C 1 g

D 50 g

Question 14 (2 MARKS)

Explain why using a measuring device that has smaller measuring increments can decrease the uncertainty in measurements taken using the measuring device.

Question 15 (2 MARKS)

Explain why ensuring measuring devices are properly calibrated can increase the accuracy of measurements.

Question 16 (8 MARKS)

Gen and Jana perform an experiment and measure the voltage across a resistor. The true value of the voltage is 4.2 V.

	Trial 1	Trial 2	Trial 3	Trial 4
Gen	4.0 V	4.5 V	3.6 V	4.3 V
Jana	3.8 V	4.1 V	4.2 V	3.9 V

a Calculate the average of Gen's results and the average of Jana's results. (2 MARKS)

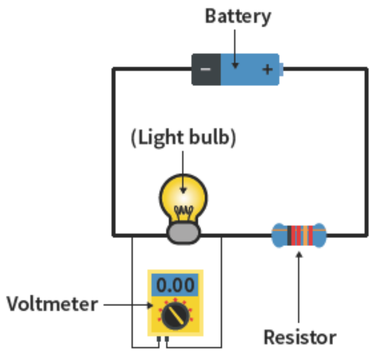
b Calculate the range of Gen's results and the range of Jana's results. (2 MARKS)

c Comment on the relative accuracy of Gen and Jana's results. (2 MARKS)

d Comment on the relative precision of Gen and Jana's results. (2 MARKS)

Question 17 (6 MARKS)

Gwen designs an experiment to determine how the voltage drop across a lightbulb in a series circuit varies with the resistance of the lightbulb. The circuit also contains a resistor.



Consider the options below and indicate which options (when added individually to this experimental design) would result in the experiment (including experimental method, analysis, and conclusions) being invalid.

Note: knowledge of electricity and circuits is not required to answer this question

I The resistance of the light bulb being tested is varied between 5 Ω and 20 Ω in 5 Ω intervals.

II An 8 V battery is used for all trials.

III The voltage of the battery is changed for the 20 Ω lightbulb test to a 6 V battery.

IV Measurements of the voltage are taken three times for each light bulb and then averaged.

V The resistance of the resistor is changed during trials of the 10 Ω light bulb.

VI Gwen notices the display on the voltmeter flicks between a few values before settling down when she turns the circuit on, so she chooses the value that seems closest to her experimental prediction.

VII The voltmeter used dies halfway through the experiment and is switched out for a different model of voltmeter.

VIII Data is analysed to plot resistance on the horizontal axis and voltage drop on the vertical axis.

IX An obvious outlier result is excluded from the data in Gwen's report and left unmentioned.

X Gwen concludes that a bigger voltage drop across the light bulb causes the resistance of the light bulb to be greater.

XI Another student, Adam, is able to repeat Gwen's experiment and produce the same results.

1D REPRESENTING AND ANALYSING DATA

The analysis stage of a scientific investigation is when conclusions about the world can be made. It involves the identification of trends in data, making allowances for errors and uncertainties, in order to determine the nature of the relationship (if any exists) between the dependent variable and the independent variable. This lesson explores the conventions of graphing data and drawing lines and curves of best fit. Understanding these conventions is critically important for clearly and correctly communicating the data from a scientific investigation.

1A Asking questions, identifying variables, and making predictions	1B Scientific conventions	1C Collecting data	1D Representing and analysing data	1E Gradients of lines of best fit

Study design dot points

- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the conventions of scientific report writing including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references

Key science skills dot point

- organise, present and interpret data using tables, line graphs, correlation, line of best fit, calculations of mean and fitting an appropriate curve to graphical data, including the use of error bars on graphs

Key knowledge units

Plotting data	2.3.4.3 & 2.3.8.3
Drawing lines and curves of best fit	2.3.4.4 & 2.3.6.1

No previous or new formulas for this lesson

Definitions for this lesson

curve of best fit a curved line that indicates the relationship between the independent and dependent variables on a graph. It must pass through the uncertainty bars of all data points

line of best fit a straight line that indicates the relationship between the independent and dependent variables on a graph. It must pass through the uncertainty bars of all data points

linearise the process of transforming data through mathematical operations so that, when graphed, a line of best fit can be drawn through the data

trendline see line of best fit or curve of best fit

Plotting data 2.3.4.3 & 2.3.8.3

OVERVIEW

Graphs can be plotted from tables of data. There are conventions that should be followed for labelling the graph, choosing a scale for each axis, and plotting uncertainty bars. Data can also be linearised before it is graphed to help understand the relationship between variables.

THEORY DETAILS

Generating a table of data

To collect data we must:

- take multiple trials of each measurement.
- average these measurements so there is one dependent result for each tested quantity of the independent variable.
- calculate uncertainties of the final values appropriately using the 'uncertainty in the average of multiple measurements' process discussed in Lesson 1C.

This data should be represented in a table.

To explore these concepts, we use the example of an experiment that investigates the relationship between the time it takes for a block to slide down a ramp and the angle of the ramp. The length of the ramp is fixed at 1.0 metre and the block starts from rest. The data for this example is shown in Table 1.

Table 1 Data collected and analysed in an experiment investigating how the time for a block to slide down a ramp varies with the angle of the ramp

Angle (±5°)	Time for block to slide down ramp (±0.1 s)			Average time (s)
	Trial 1	Trial 2	Trial 3	
10	3.2	3.5	3.4	3.4 ± 0.2
20	2.4	2.5	2.4	2.4 ± 0.1
30	1.8	2.1	2.0	2.0 ± 0.2
40	1.8	1.8	1.7	1.8 ± 0.1
50	1.5	1.7	1.6	1.6 ± 0.1
60	1.4	1.5	1.5	1.5 ± 0.1

We use the table to create a list of points that should be graphed to analyse the relationship between the independent variable and dependent variable. The first listed coordinate in a point corresponds to the independent variable and the second corresponds to the dependent variable.

In this example, the independent variable is the angle of the ramp and the dependent variable is the average time for the block to slide down the ramp. As such, the points to be plotted are:

(10, 3.4), (20, 2.4), (30, 2.0), (40, 1.8), (50, 1.6), (60, 1.5).

Graphing conventions

There are several conventions that must be followed to correctly represent scientific data on a graph.

Labelling:

- **The independent variable should be plotted on the horizontal axis.**
- **The dependent variable should be plotted on the vertical axis.**
- The variables should be **labelled on the relevant axis with their respective units.**
- The graph title should generally be of the form '[dependent variable] versus [independent variable]'.

Scales on axes:

- Each axis should have a **consistent scale** so that the intervals between grid lines on an axis represents a constant value.
- The scale on each axis should be chosen so that the **data points take up the majority of the available graph space** (the data points should cover more than 50% of each axis).
- The axis can (but does not have to) indicate a power of ten on the scale by which all values on that axis should be multiplied.

USEFUL TIP

In an exam, marked axes and a grid will be provided but you will usually need to choose an appropriate scale. When answering graphing questions from this book, it is suggested to sketch answers on graph paper to get practice in choosing an appropriate scale to fit a given grid and data set.

Using uncertainty bars

An uncertainty bar (or error bar) is a line with an end cap that indicates the size of the uncertainty in a given value. Horizontal uncertainty bars are the uncertainty in the independent variable and vertical uncertainty bars are the uncertainty in the dependent variable. The combination of the horizontal and vertical uncertainty bars indicates a rectangular area where the 'true' value may be.

The uncertainty value quoted is added to both sides of the point so that the distance between the two end caps of an uncertainty bar is twice the uncertainty. If measurement uncertainties are stated, uncertainty bars should be plotted on the graph.

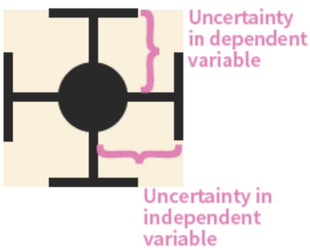


Figure 1 An example point with horizontal and vertical uncertainty bars. The yellow area indicates a range where the 'true' value might be located.

Using these principles, an appropriate graph for the data from Table 1 is shown in Figure 2.

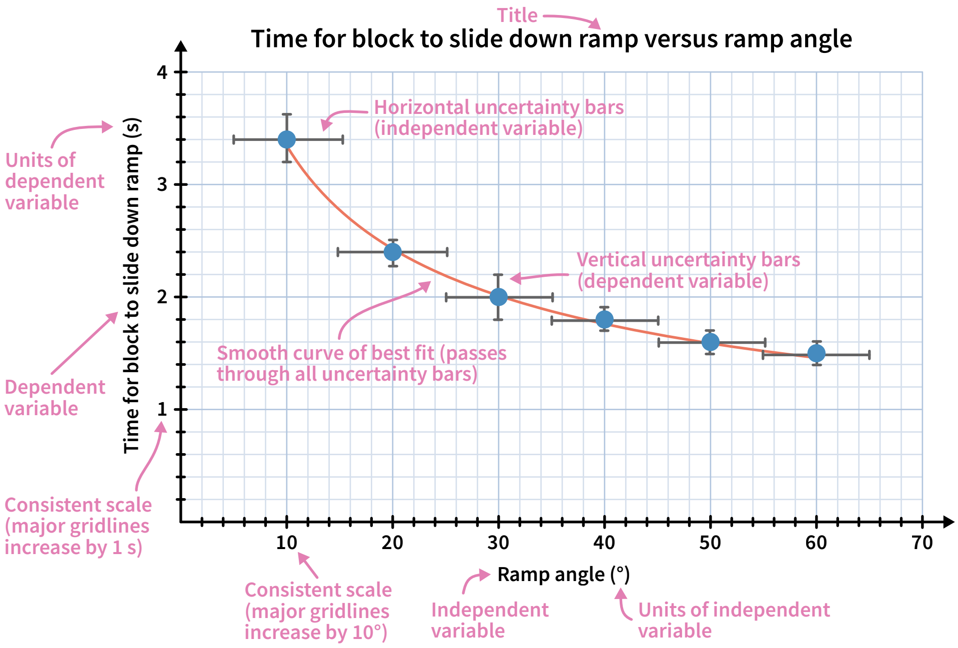


Figure 2 An annotated graph of the data from Table 1

Linearising data

Linearising data is the process of transforming one or both of the independent and dependent values so that, when graphed, the points have a line of best fit. This is valuable because it can help us to determine the mathematical form of an unknown relationship between two variables.

Examples of how a variable (x) can be transformed include raising it to a power (x^2), taking the square root ($\sqrt{x}$) or taking the reciprocal ($\frac{1}{x}$) can be seen in Figure 3. Note that linearised graphs do not need to trend towards the origin as these ones do.

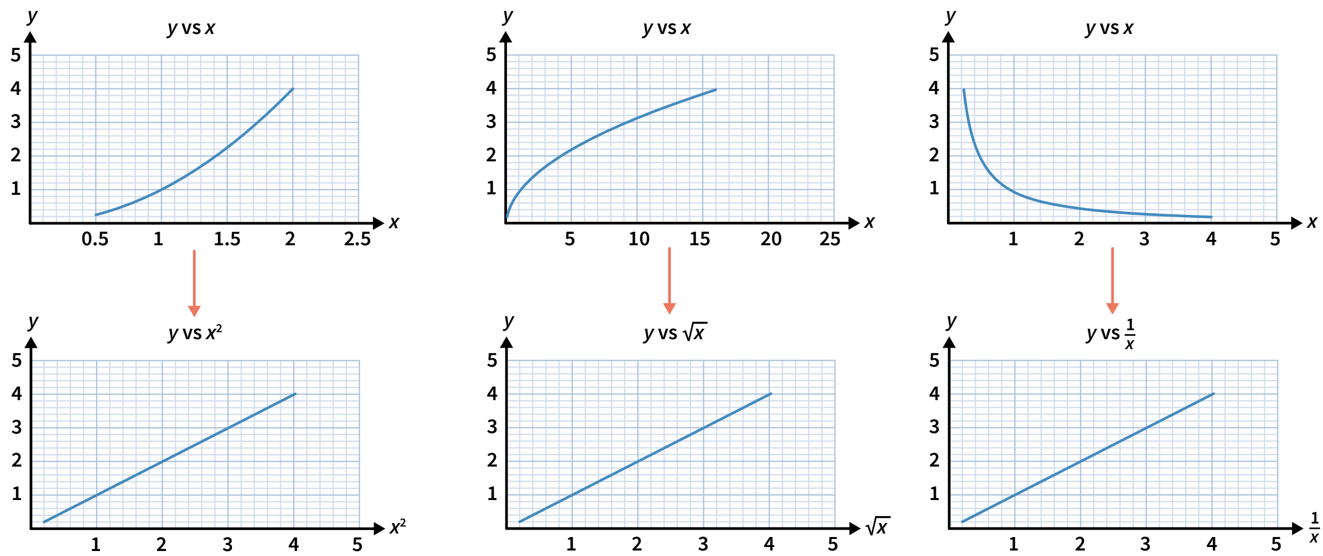


Figure 3 Examples of how different graphs can be linearised by transforming the independent variable. A straight line of best fit that passes through the origin means that the variables on the axes are proportional to each other.

If a variable is transformed appropriately and the result is a linear relationship, this indicates a proportionality relationship between the variables plotted. For example, if there is a straight line of best fit when a variable y is graphed against the square root of another variable ($\sqrt{x}$), we can write that $y \propto \sqrt{x}$ or $y = k\sqrt{x}$ (where k is a constant, which represents the gradient of the linearised graph). Note that similar transformations can be made to the dependent variable in order to linearise data and establish a relationship such as $\sqrt{y} \propto x$.

Worked example 1

A student collected data on the distance travelled (d) by a ball that starts from rest and rolls down a ramp for different amounts of time (t). The angle of the ramp is fixed.

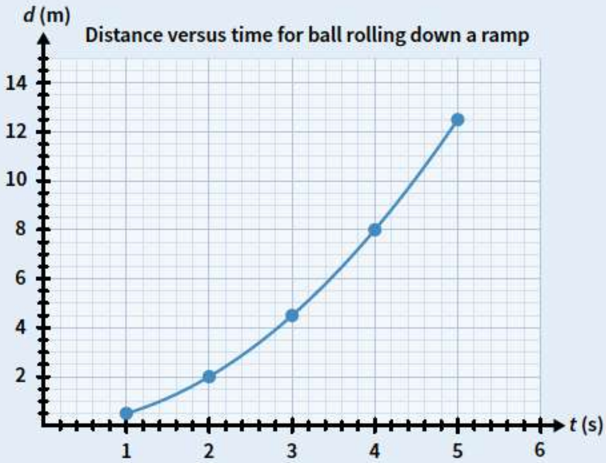
a Plot a graph of the data with a curve of best fit. Assume the uncertainty in distance and time are negligible.

b Linearise the data and plot a graph to show that $d \propto t^2$.

Time, t (s)	Distance, d (m)
1.0	0.5
2.0	2.0
3.0	4.5
4.0	8.0
5.0	12.5

Working

a



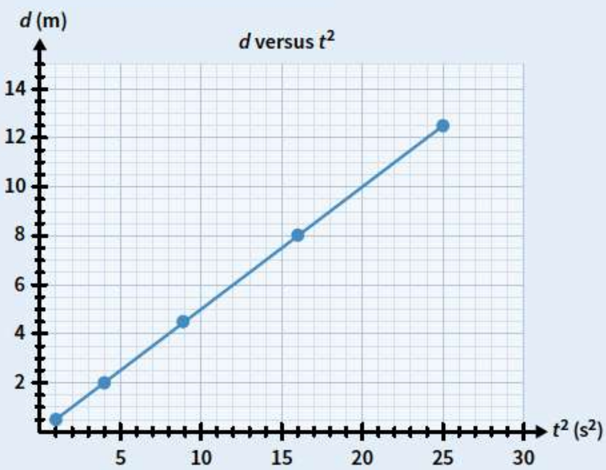
Process of thinking

Plot the data from the included table with time on the horizontal axis and distance on the vertical axis.

b

t^2 (s^2)	Distance d (m)
1.0	0.5
4.0	2.0
9.0	4.5
16	8.0
25	12.5

To linearise the data, calculate the values of t^2. Ensure that the units undergo the same transformation (s becomes s^2).



Plot the data from the new table with time squared on the horizontal axis and distance on the vertical axis.

Drawing lines and curves of best fit 2.3.4.4 & 2.3.6.1

OVERVIEW

Lines of best fit and curves of best fit are straight and curved lines respectively that indicate the relationship between the independent and dependent variables on a graph. To be a valid indicator of the relationship between variables, a line or curve of best fit must pass through the uncertainty bars of all points.

THEORY DETAILS

A line or curve of best fit indicates the relationship between two variables. Lines and curves of best fit can also be called 'trendlines'.

Lines and curves of best fit must meet the following requirements:

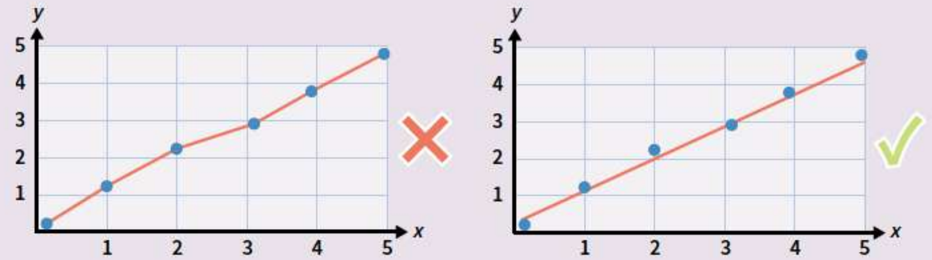
- Must pass through the uncertainty bars of all points (it does not need to pass through the specific data point)
- Should be smooth
- Should not be forced to pass through the origin
- Should not be forced to pass through the first and/or last point (or any point on the graph)
- Should not extend significantly beyond the region of the points

The reason for not forcing the line or curve of best fit through the origin, first point, or last point is that all data points are equally important. Forcing it through one of these points would incorrectly give that point more importance than the other data points when determining the overall trend.

A line or curve of best fit that does not pass through the origin when it is expected to do so can indicate a systematic error in the experiment.

USEFUL TIP

When using a computer program to create a graph, choose a 'scatter plot' and then add a trendline. Do not choose a plot that connects the data points dot-to-dot.



If a straight line cannot be drawn so that it passes through all the uncertainty bars, there cannot be a line of best fit, so the trend would be better represented by a curve of best fit (see Figure 4). If a line of best fit can be drawn, it indicates that the data may have a linear relationship, but it is also possible that the uncertainty is too great or the spread of data is too small to establish the true relationship.

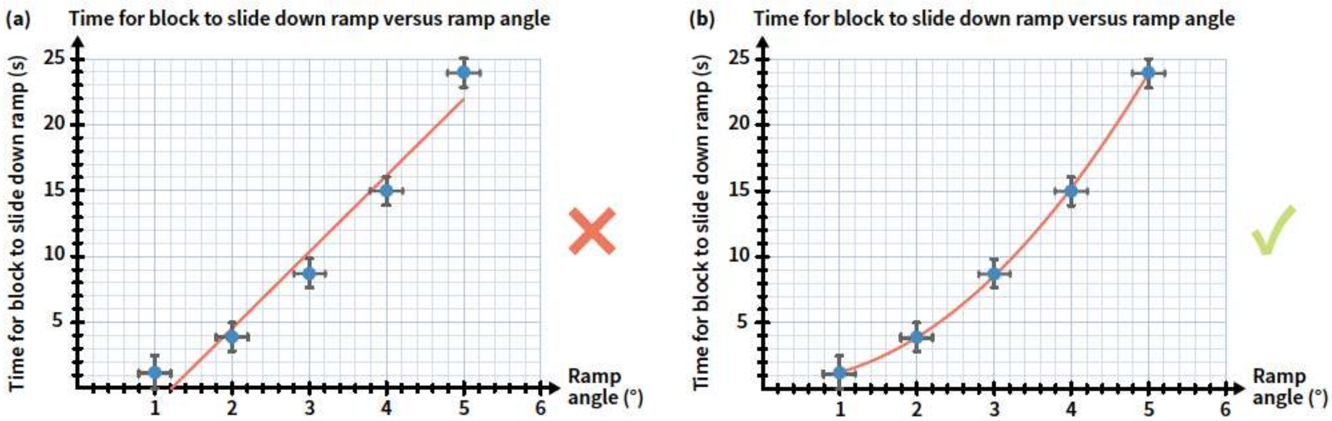


Figure 4 **(a)** The line of best fit is not valid as it does not pass through the uncertainty bars of all points. **(b)** The curve of best fit is valid as it passes through the uncertainty bars of all points.

Theory summary

Graph labelling:

- The independent variable should be plotted on the horizontal axis.
- The dependent variable should be plotted on the vertical axis.
- The variables should be labelled on the relevant axis with their respective units .
- The graph title should generally be of the form 'dependent variable versus independent variable'.

Scales on axes:

- Each axis should have a consistent scale so that the intervals between grid lines on an axis represents a constant value.
- The scale on each axis should be chosen so that the data points take up the majority of the available graph space.
- The axis can (but does not have to) indicate a power of ten on the scale by which all values on that axis should be multiplied.

Line and curve of best fit requirements:

- Must pass through the uncertainty bars of all points (it does not need to pass through the specific data point)
- Should be smooth
- Should not be forced to pass through the origin
- Should not be forced to pass through the first and/or last point (or any point of the graph)
- Should not extend significantly beyond the region of the points

1D Questions

THEORY REVIEW QUESTIONS

Question 1

When creating a graph of data, which of the following is **incorrect**?

A The independent variable should be plotted on the vertical axis.

B The variables should be labelled on their respective axis with units.

C The axes should have consistent scales.

D The scale on the axes should be chosen such that the data points take up the majority of the available graph space.

Question 2

Which of the following statements is true regarding uncertainty bars?

A Vertical error bars indicate the uncertainty in the independent variable.

B The 'true' value should lie in the area indicated by the uncertainty bars.

C The distance between the two end caps of an uncertainty bar is the magnitude of the uncertainty.

D In general, uncertainty bars do not need to be included on graphs in physics.

Question 3

Physicists have determined that the power (P) dissipated in a resistor of fixed resistance (R) as the voltage (V) across the resistor is varied can be calculated using the formula $P = \frac{V^2}{R}$. A student is testing this theory and wants to linearise their data. Which of the following would successfully result in a graph that has a line of best fit? *(Select all that apply)*

I P vs V

II P vs V^2

III $\sqrt{P}$ vs V

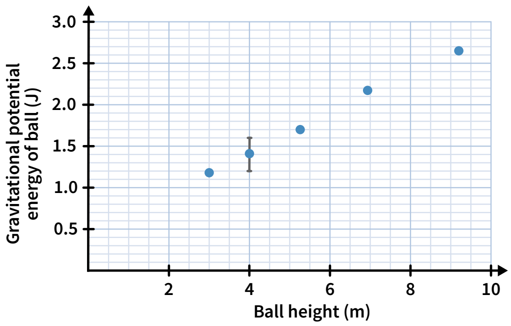
IV $\sqrt{P}$ vs V^2

EXAM-STYLE QUESTIONS

This lesson

Question 4 (3 MARKS)

A student is plotting a graph of the gravitational potential energy of a ball versus the height it is lifted above the ground. The uncertainty in measuring the height is negligible and the constant uncertainty in measuring the gravitational potential energy is indicated on one graphed data point.



a Describe the steps that must be taken to determine if this graph can have a line of best fit. (2 MARKS)

b Use the process you described in part **a** to determine if this graph can have a line of best fit. (1 MARK)

Adapted from 2017 VCAA Sample Exam Q17f

Question 5 (5 MARKS)

Duncan and Arushi are studying the radioactive decay of phosphorus-32. They record the data shown in the table.

Time elapsed (days)	Uncertainty in time (days)	Phosphorus-32 mass (g)	Uncertainty in phosphorus-32 mass (g)
0	±1	100	±5
11	±1	60	±5
27	±1	28	±5
52	±1	8	±5

Using this data:

- Plot a graph of the phosphorus-32 mass versus the time elapsed.
- Include uncertainty bars for each data point.
- Draw a curve of best fit.
- Include appropriate labels and scales for both axes.

Question 6 (5 MARKS)

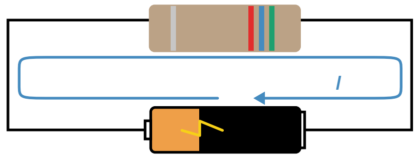
Fatima is running on a track that has a marking every 10 m. Her friend records the time in seconds that it takes her to run 100 metres, noting roughly the time it takes for her to pass each 10 m mark on the track.

Distance, d (m)	Time, t (±1 s)
10	2
20	4
30	7
40	11
50	14
60	18
70	23
80	28
90	34
100	41

Draw a graph of this data with uncertainty bars and a line or curve of best fit as appropriate.

Question 7 (12 MARKS)

Maneesha studies the current I passing through a resistor of resistance R in a circuit connected to a 1.5 V AA battery. Maneesha believes that $I \propto \frac{1}{R}$.



Resistance, R (Ω)	Uncertainty in resistance, R (Ω)	Current, I (A)	Uncertainty in current, I (A)
0.50	±0.05	3.0	±0.1
1.00	±0.05	1.5	±0.1
1.50	±0.05	1.0	±0.1
2.00	±0.05	0.8	±0.1
2.50	±0.05	0.6	±0.1
3.00	±0.05	0.5	±0.1

a Plot a graph of the data recorded in the table above. Include uncertainty bars and a curve of best fit as appropriate. (5 MARKS)

b Calculate the values of $\frac{1}{R}$ and hence plot the graph of I versus $\frac{1}{R}$. Include vertical uncertainty bars (horizontal uncertainty bars are not required), and include a line or curve of best fit as appropriate. (6 MARKS)

c Is Maneesha's hypothesis that $I \propto \frac{1}{R}$ supported by her experimental data? (1 MARK)

Question 8 (13 MARKS)

Aditya is investigating the relationship between the length of a ramp (l) measured in metres, held at a fixed angle, and the time it takes a toy truck to travel down the ramp (t) measured in seconds.

His hypothesis is that $t \propto \sqrt{l}$. He records the following data:

Length of ramp, l (±0.1 m)	Time, t (±0.02 s)
1.0	0.68
2.0	0.96
3.0	1.16
4.0	1.34
5.0	1.50

a Plot a graph of time versus length based on the data recorded in the table above. Include uncertainty bars and a line or curve of best fit as appropriate. (5 MARKS)

b Transform this data by calculating values of $\sqrt{l}$ and hence plot a graph that could support Aditya's hypothesis. Only plot vertical uncertainty bars, and include a line or curve of best fit as appropriate. (6 MARKS)

c Is Aditya's hypothesis that $t \propto \sqrt{l}$ supported by the data? Explain your answer with reference to a graph created in either part **a** or part **b**. (2 MARKS)

1E GRADIENTS OF LINES OF BEST FIT

The gradient of data that displays a linear relationship is often a physically significant value which represents the constant rate of change between the two quantities being analysed. This lesson explains how to correctly calculate the gradient from experimental data, and how to interpret the physical meaning of a gradient.

1A Asking questions, identifying variables, and making predictions	1B Scientific conventions	1C Collecting data	1D Representing and analysing data	1E Gradients of lines of best fit

Study design dot point

- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies

Key science skills dot points

- process quantitative data using appropriate mathematical relationships, units and number of significant figures
- organise, present and interpret data using tables, line graphs, correlation, line of best fit, calculations of mean and fitting an appropriate curve to graphical data, including the use of error bars on graphs

Key knowledge units

Calculating the gradient of a line of best fit	2.3.4.5
The meaning of a gradient	2.3.4.6

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$gradient = \frac{y_2 - y_1}{x_2 - x_1}$ gradient of a straight line

Definitions for this lesson

gradient the graphical representation of the rate of change of one variable with respect to another

Calculating the gradient of a line of best fit 2.3.4.5

OVERVIEW

On a graph, the gradient (or slope) is the ratio of the change in the variable on the vertical axis to the change in the variable on the horizontal axis. When a line of best fit is appropriate for a set of data, the gradient should be calculated from points on the line rather than from specific data points.

THEORY DETAILS

Straight line graphs have a constant gradient, which means that the dependent variable (on the vertical axis) will increase or decrease by a fixed amount for every unit increase in the independent variable (on the horizontal axis). Consider Figure 1, which shows the speed of an object that has been released from rest and is in free fall without air resistance. The object's speed increases by a fixed amount, 9.8 m s^{-1}, for each second that passes. This means the gradient is 9.8 m s^{-2} $\left(\frac{9.8\ \text{m s}^{-1}}{1\ \text{s}}\right)$. So when the time increases by 5.0 seconds, the speed increases by $5.0 \times 9.8 = 49$ m s^{-1}.

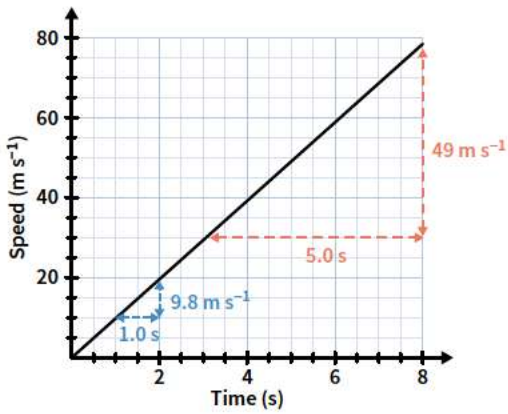


Figure 1 Speed vs time graph for an object in free fall without air resistance

We can calculate the gradient of a straight line from two points on the line:

$$gradient = \frac{y_2 - y_1}{x_2 - x_1}$$

(x_1, y_1) = a point on the line of best fit, (x_2, y_2) = another point on the line of best fit

The change in the vertical axis values $(y_2 - y_1)$ is often called the 'rise' and the change in the horizontal axis values $(x_2 - x_1)$ is often called the 'run'.

There are some important points to emphasise for calculating the gradient of a line of best fit:

- We should choose points that are far apart. This reduces the effect of any errors that we make when reading the points from the graph, which improves the accuracy of the gradient calculation. This is shown in Figure 2, where the red and blue data points have the same error when compared to the 'true' values, but the gradient that would be calculated using the blue data points is more accurate than the gradient that would be calculated using the red data points.
- We should ignore the measured data points and use only points that are on the line of best fit.
- Check the scale on each axis and apply a scale factor if applicable (see Worked Example 1).
- The units of the gradient are given by $\frac{\textit{units on vertical axis}}{\textit{units on horizontal axis}}$.

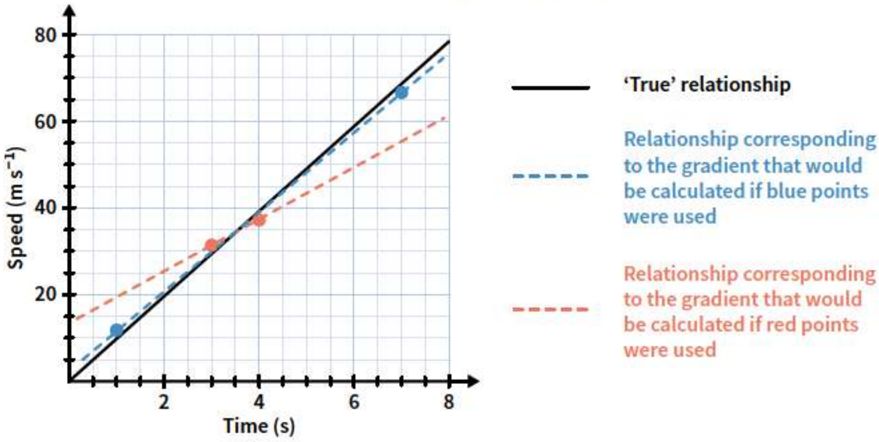
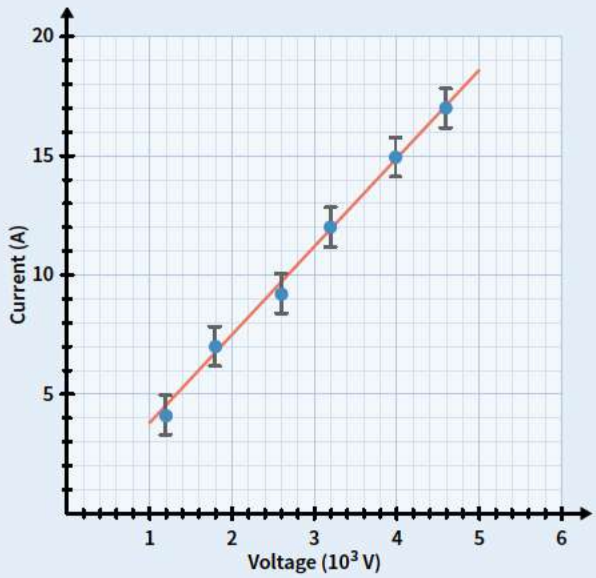


Figure 2 A small error when reading points from a graph can lead to a large error in the calculation of the gradient if the two points are close together.

Worked example 1

Find the gradient of this current versus voltage graph.



Working

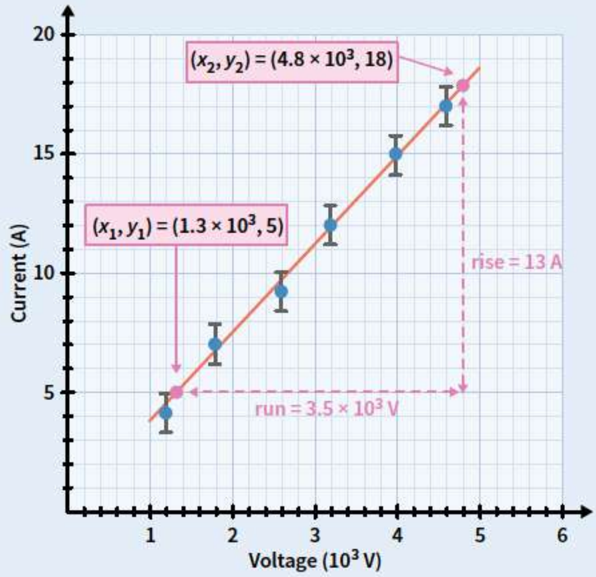
$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{18 - 5}{(4.8 - 1.3) \times 10^3}$

$gradient = 3.7 \times 10^{-3}$ A V^{-1}

Process of thinking

Pick two points on the line that are far apart and use them to calculate the gradient.

Remember to include the scale factor on the horizontal axis when calculating the run.



The units of the gradient are given by $\frac{units\ on\ vertical\ axis}{units\ on\ horizontal\ axis} = \frac{A}{V}$.

The meaning of a gradient 2.3.4.6

OVERVIEW

A gradient is a rate of change. For a line of best fit for physical data, this rate of change often represents a meaningful physical quantity.

THEORY DETAILS

In its most general form:

- A positive gradient means that, when the independent variable increases, the dependent variable also increases.
- A negative gradient means that, when the independent variable increases, the dependent variable decreases.
- The greater the magnitude of the gradient, the more the dependent variable will increase (or decrease) per unit increase in the independent variable.

The gradient represents the change in the vertical axis variable divided by the change in the horizontal axis variable $\left(gradient = \frac{\Delta y}{\Delta x}\right)$. If it is known that the line passes through the origin, then this is equivalent to the vertical axis variable divided by the horizontal axis variable $\left(gradient = \frac{y}{x}\right)$. We can determine the physical meaning of a gradient from an equation relating the two variables and the context of the physical situation.

From Figure 1, $gradient = \frac{change\ in\ speed}{change\ in\ time} = \frac{\Delta v}{\Delta t}$. We also know that the magnitude of acceleration is given by $a = \frac{\Delta v}{\Delta t}$. Therefore we can conclude that the gradient in Figure 1 is equal to the magnitude of acceleration.

USEFUL TIP

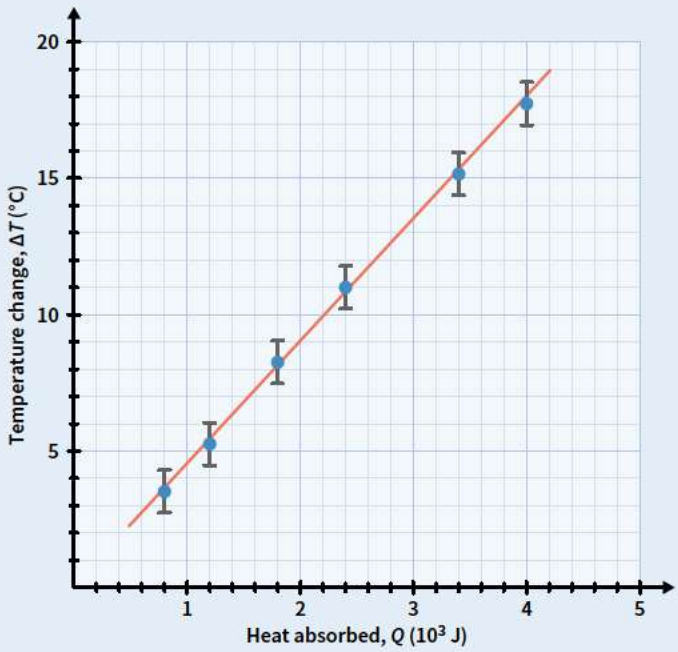
It is common for an exam question to ask us to use the gradient from a line of best fit to determine the experimental value of a known constant. It is important that we do use the gradient of the line of best fit for the experimental data in these cases, rather than the known value.

Worked example 2

The change in temperature, ΔT (measured in degrees celsius, °C), of an object that absorbs some heat, Q (measured in joules, J), can be calculated from the equation $\Delta T = \frac{Q}{mc}$, where m is the mass of the object in kilograms and c is the specific heat capacity of the object, measured in J kg^{-1} °C^{-1}.

Scientists undertake an experiment where they measure the temperature change of an object with a mass of 2.0 kg as it is heated. They plot the data for ΔT against Q and draw a line of best fit as shown. The line of best fit has a gradient of 4.5×10^{-3} °C J^{-1}.

Use the gradient to calculate the value of the specific heat capacity, c.



Working

$gradient = \frac{\Delta T}{Q} = \frac{1}{mc}$

$4.5 \times 10^{-3} = \frac{1}{2.0 \times c}$

$c = \frac{1}{2.0 \times 4.5 \times 10^{-3}} = 1.1 \times 10^{2}$ J kg^{-1} °C^{-1}

Process of thinking

The gradient represents $\frac{\textit{vertical axis variable}}{\textit{horizontal axis variable}}$.

Rearranging $\Delta T = \frac{Q}{mc}$ gives $\frac{\Delta T}{Q} = \frac{1}{mc}$.

$gradient = 4.5 \times 10^{-3}$ °C J^{-1}, $m = 2.0$ kg

Due to the uncertainty bars of each data point, there are a range of possible lines of best fit which could be used with a range of gradients. Hence there are a range of possible values for c.

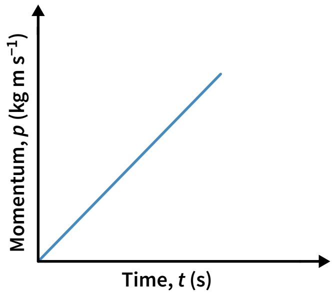
Theory summary

- Gradients can be calculated by finding two points on the line of best fit and substituting them into the formula: $gradient = \frac{y_2 - y_1}{x_2 - x_1}$.
  - Points should be chosen that are far apart on the line.
- By dividing the variables of the vertical axis by those of the horizontal axis, we can determine what the gradient represents.

1E Questions

THEORY REVIEW QUESTIONS

Use the following graph to answer Questions 1–3.



Question 1

Which of the following expressions does the gradient of this graph represent?

A $\Delta p \times \Delta t$

B $p + t$

C $\frac{t}{p}$

D $\frac{\Delta p}{\Delta t}$

Question 2

Which of the following units should be used for the gradient of this graph?

A kg m s^{-2}

B kg

C kg s

D kg m

Question 3

It is known that $\Delta p = F\Delta t$, where F is the force acting on the object being measured. Determine which of the following expressions the gradient of the graph also represents.

A F

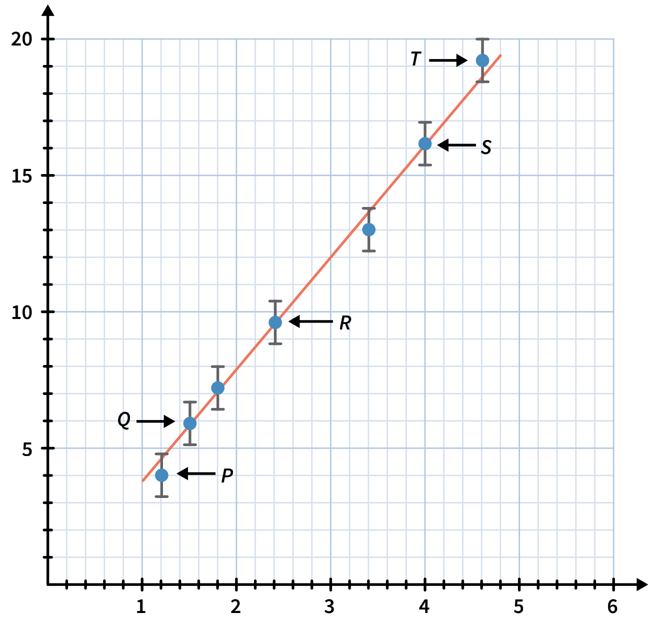
B $\frac{1}{F}$

C $\frac{F}{\Delta t}$

D $\frac{F}{\Delta p}$

Question 4

Which two data points from those identified on the graph (P, Q, R, S, and T) would be the best choice to calculate the gradient of the line of best fit?



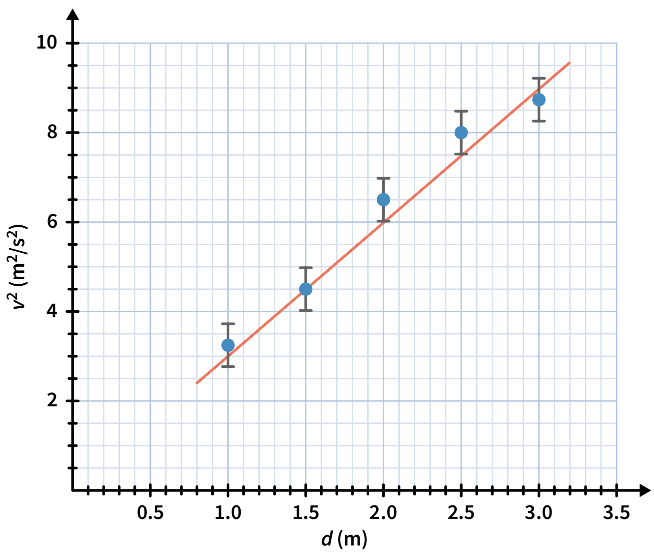
EXAM-STYLE QUESTIONS

This lesson

Question 5 (4 MARKS)

A cart starts from rest and accelerates at a constant rate in a straight line. Its speed is measured at particular distances from its starting position. It is known that the speed, v (m s^{-1}), relates to the distance travelled, d (m), by the equation $v^2 = 2ad$, where a is the magnitude of the acceleration (m s^{-2}).

The data is plotted on a graph with d on the horizontal axis and v^2 on the vertical axis. A line of best fit is drawn through the data as shown.



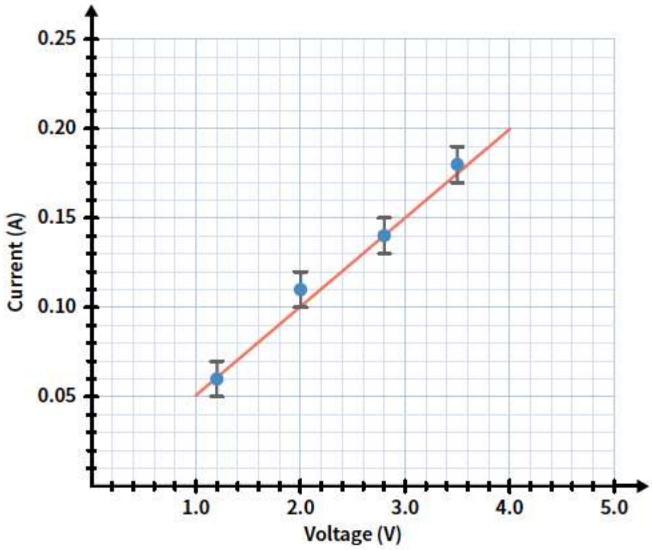
a Calculate the gradient of the line of best fit. (2 MARKS)

b Use the gradient of the line of best fit to calculate the value of a determined in this experiment. (2 MARKS)

Question 6 (4 MARKS)

Students measure the electric current passing through a particular device with a constant electrical resistance when different voltages are connected across the device. For a device with a constant electrical resistance, it is known that $I = \frac{V}{R}$ where I is the current measured in amps (A), V is the voltage measured in volts (V), and R is the resistance measured in ohms.

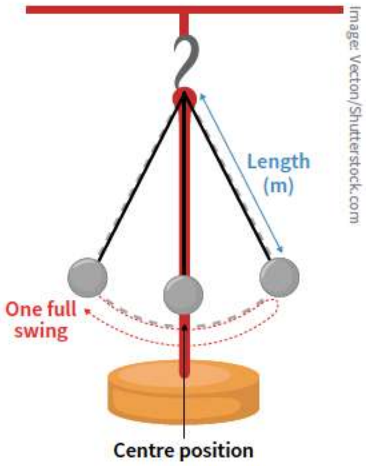
The data is plotted on a graph with voltage on the horizontal axis and current on the vertical axis. A line of best fit is drawn through the data as shown.



Use the gradient of the line of best fit to calculate the experimentally determined resistance of the device, R.

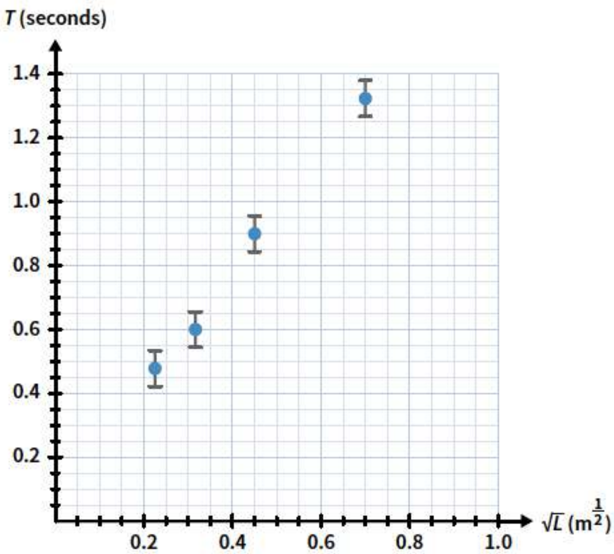
Question 7 (6 MARKS)

Students conduct an experiment in which they measure the period (the time taken to complete one full swing and return to the same position) of a pendulum of varying lengths.



It is known that the relationship between the length of a pendulum, L (measured in metres, m), and its period, T (measured in seconds, s), is approximated by $T = 2\pi\sqrt{\frac{L}{g}}$, where g is the magnitude of the acceleration due to gravity ($m\ s^{-2}$).

The students plot T against $\sqrt{L}$ to obtain a line of best fit. The uncertainty in the period measurements is ±0.5 seconds. Note that the lengths are measured to a high level of confidence.



a Copy the graph and draw a line of best fit. (2 MARKS)

b Use the line of best fit to calculate the magnitude of the acceleration due to gravity. (4 MARKS)

CHAPTER 1 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

A model is best described as

A a prediction that can be tested through experimentation.

B only useful as a teaching tool.

C a representation of a physical process that cannot be directly experienced.

D an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation.

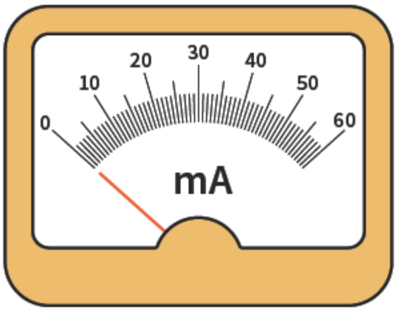
Question 2

According to the rules of significant figures and decimal places, determine which of the following is the correct value of the expression: $5.124 \times 10^{10} - 1.2 \times 10^{9}$

A 3.9×10^{10} **B** 5.00×10^{10} **C** 5.004×10^{10} **D** 3.92×10^{10}

Question 3

A student is writing the results from an experiment using the ammeter shown in the provided diagram. What uncertainty should be recorded when reading data from this device?



A ±0.5 mA

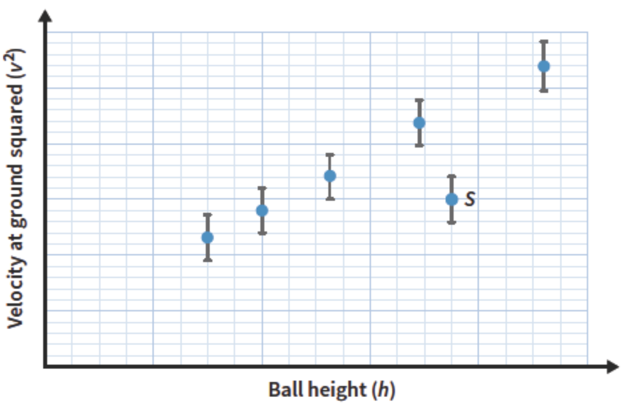
B ±0.5 A

C ±1.0 mA

D ±1.0 A

Use the following information to answer Questions 4 and 5.

Mike is conducting an experiment relating the height a ball is dropped from to its velocity when it reaches the ground. He collects his data using reliable methods and plots the following graph.



Question 4

Mike's plot has one data point, *S*, that prevents him from drawing a line of best fit to match the data. Mike remembers that when he was recording the time for that data point he got distracted by a classmate and made his measurement after the ball had bounced off the ground. Select Mike's best choice in how to treat point *S* as he attempts to draw a line of best fit.

A Draw a line of best fit for the other data but leave point *S* on the graph.

B Draw a line from the centre of each point to the next, including point *S*.

C Discard all of his data and repeat the experiment as the presence of irregular data, such as point *S*, proves that the rest of the data is unreliable.

D Disregard point *S* and remove it from the graph, then draw a line of best fit through the remaining data.

Question 5

We can relate the height an object is released from, h, to its velocity squared at the ground, v^2, through the equation $gh = \frac{1}{2}v^2$ where g is the acceleration due to gravity. Assuming that a line of best fit is valid, determine what the gradient of the line of best fit of Mike's data would represent.

A $2g$, twice the acceleration due to gravity

B g, the acceleration due to gravity

C t, the time the ball would take to fall

D h, the original height the ball was dropped from

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (5 MARKS)

A team of scientists have been employed by *Big Smoke Ltd.*, the world's largest fictional cigarette company, to determine the effects of smoking cigarettes on beard growth. After their first meeting the scientists return with a statement about the experiment they will perform, stating:

"We expect that increased smoking of cigarettes will have a negligible effect on the growth of a beard but may have consequences for the chemical makeup of the beard's hair follicles."

a Is this statement an example of a scientific model, theory, or hypothesis? Justify your answer. (2 MARKS)

b After the experiment was conducted the scientists concluded:

"Smoking cigarettes had a positive effect on both the growth and health of beards."

However, a *60 Seconds* report on the study revealed that the scientists were given $10 000 each if their experiment produced results supporting the idea that smoking has positive outcomes for beard growth.

Using this information, comment on the validity of the study. (3 MARKS)

Question 7 (14 MARKS)

Cathal wants to determine the amount of energy it takes to heat samples of metal from room temperature (22°C) to 300°C. He has five different masses of scrap metal starting at 100 g and increasing in mass by 50 g increments up to 300 g. He heats each sample to 300°C three times, waiting for it to cool back to 22°C before attempting to heat it again. Cathal uses the same bunsen burner to heat each sample and records the total amount of energy it uses.

a Identify the independent and dependent variables, and one controlled variable in this experiment. (3 MARKS)

b Comment on the repeatability of Cathal's experiment and suggest one way to improve its repeatability. (2 MARKS)

Cathal records the following table of data.

Mass of metal sample (g)	Energy used (× 1.0 × 10^3 J)			
	1st attempt	2nd attempt	3rd attempt	Average
100	12.0 ± 1.0	11.0 ± 1.0	13.0 ± 1.0	12.0 ± 1.0
150	19.0 ± 1.0	19.0 ± 1.0	18.0 ± 1.0	18.7 ± 1.0
200	25.0 ± 1.0	24.0 ± 1.0	24.0 ± 1.0	24.3 ± 1.0
250	31.0 ± 1.0	32.0 ± 1.0	30.0 ± 1.0	31.0 ± 1.0
300	37.0 ± 1.0	35.0 ± 1.0	39.0 ± 1.0	37.0 ± 1.0

c On a set of axes:

- Plot a graph of metal sample mass against average energy used.
- Include uncertainty bars for each data point.
- Draw a line of best fit.
- Include appropriate scales, labels, and units for both axes. (6 MARKS)

d Considering that the theoretical value for the energy used to heat the 100 g sample is 12.4 × 10^3 J and the 150 g sample is 18.5 × 10^3 J, compare the accuracy and precision of Cathal's sets of measurements for these masses. (3 MARKS)

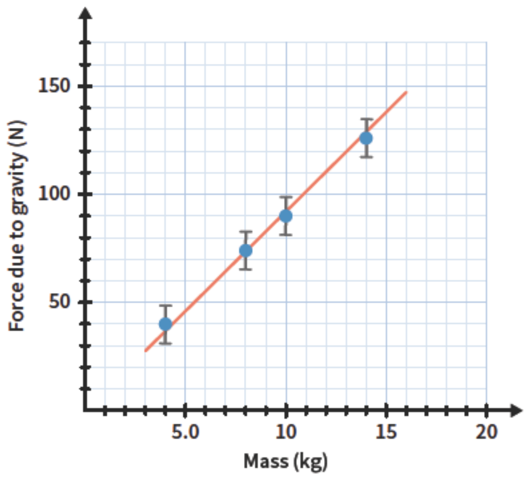
Question 8 (6 MARKS)

Enya is doing a set of experiments to measure the force due to gravity on a selection of household objects: a 4.0 kg pot plant, an 8.0 kg record-player, a 10 kg space heater, and a 14 kg humidifier. She wants to determine if the acceleration due to gravity is different in her apartment compared to the accepted value. It is known that the force due to gravity is related to mass by the equation $F_g = mg$, where F_g is the force, m is the mass, and g is the acceleration due to gravity.

a Identify the type of data Enya is collecting by performing this experiment. (1 MARK)

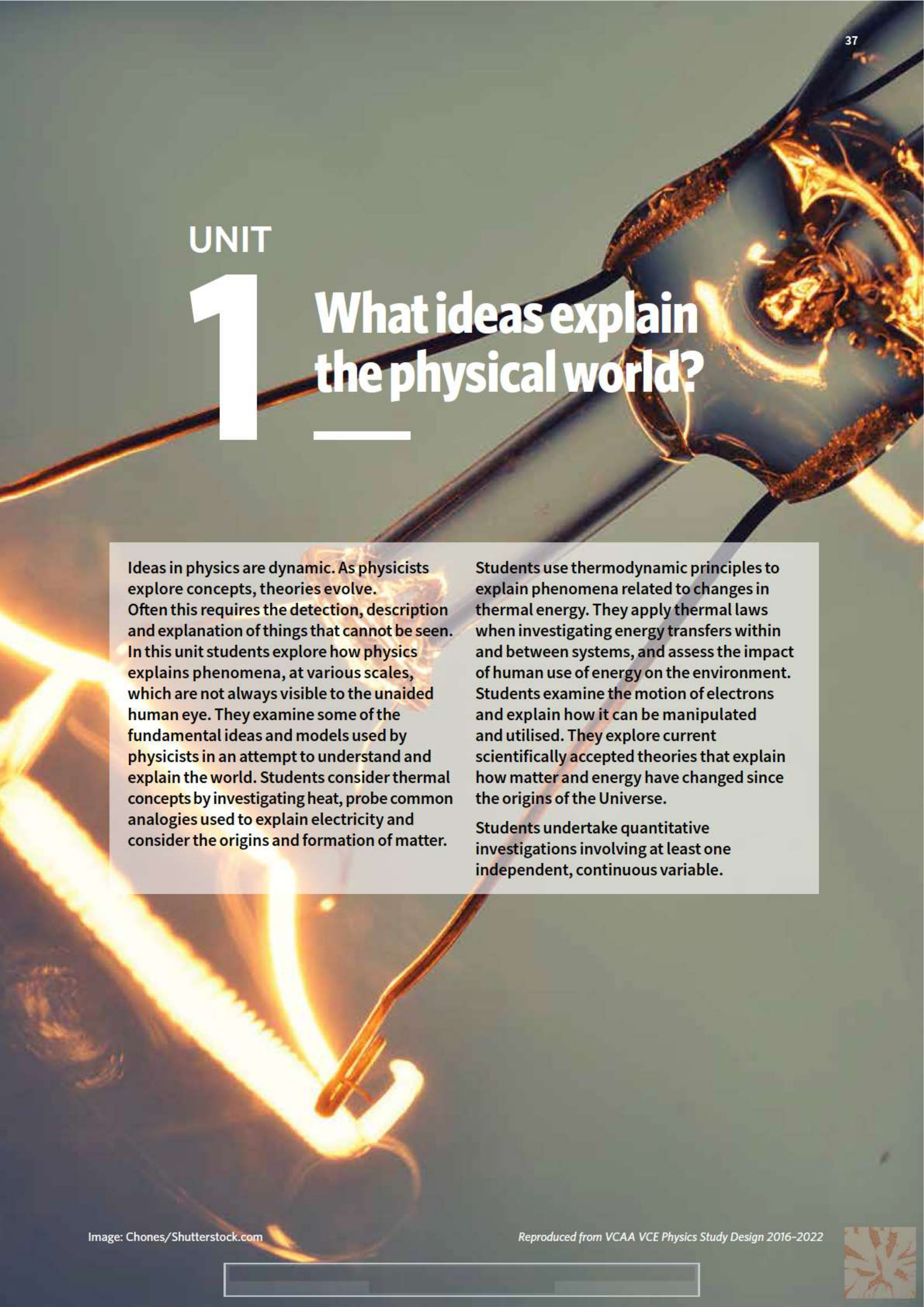
b In her first attempt to perform this experiment, all of Enya's data was 50% higher than the values she would have obtained if she had performed her experiment without error. Identify the type of error present in Enya's first attempt. (1 MARK)

c The provided graph represents Enya's second attempt at performing this experiment. She now gets results much closer to her prediction.



Use the included graph to determine the experimental value of g. (2 MARKS)

d After Enya posts on social media about her discovery that the value of g cannot be the accepted value (in her location) of 9.8 m s^{-2}, an interested group of scientists analyse her results and try to repeat the experiment. However, using the same method and test material they get the result: $g = 9.79 \pm 0.05$ N kg^{-1}. Comment on the reproducibility of Enya's experiment. (2 MARKS)



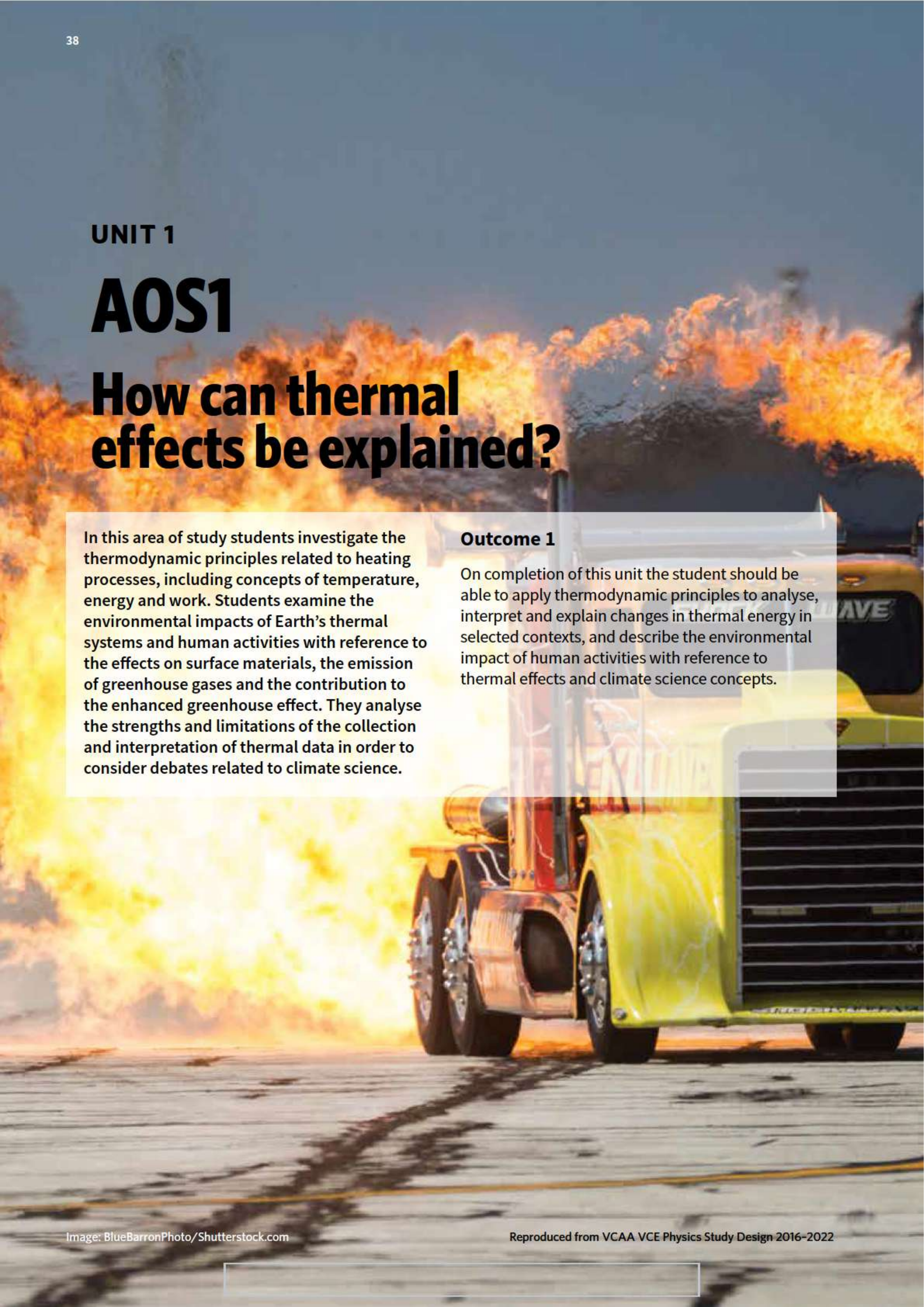
UNIT 1 What ideas explain the physical world?

Ideas in physics are dynamic. As physicists explore concepts, theories evolve. Often this requires the detection, description and explanation of things that cannot be seen. In this unit students explore how physics explains phenomena, at various scales, which are not always visible to the unaided human eye. They examine some of the fundamental ideas and models used by physicists in an attempt to understand and explain the world. Students consider thermal concepts by investigating heat, probe common analogies used to explain electricity and consider the origins and formation of matter.

Students use thermodynamic principles to explain phenomena related to changes in thermal energy. They apply thermal laws when investigating energy transfers within and between systems, and assess the impact of human use of energy on the environment. Students examine the motion of electrons and explain how it can be manipulated and utilised. They explore current scientifically accepted theories that explain how matter and energy have changed since the origins of the Universe.

Students undertake quantitative investigations involving at least one independent, continuous variable.

Image: Chones/Shutterstock.com



UNIT 1

AOS1

How can thermal effects be explained?

In this area of study students investigate the thermodynamic principles related to heating processes, including concepts of temperature, energy and work. Students examine the environmental impacts of Earth's thermal systems and human activities with reference to the effects on surface materials, the emission of greenhouse gases and the contribution to the enhanced greenhouse effect. They analyse the strengths and limitations of the collection and interpretation of thermal data in order to consider debates related to climate science.

Outcome 1

On completion of this unit the student should be able to apply thermodynamic principles to analyse, interpret and explain changes in thermal energy in selected contexts, and describe the environmental impact of human activities with reference to thermal effects and climate science concepts.

Image: BlueBarronPhoto/Shutterstock.com

UNIT 1 AOS 1, CHAPTER 2

Thermodynamics principles

02

Key knowledge

- convert temperature between degrees Celsius and kelvin
- describe the Zeroth Law of Thermodynamics as two bodies in contact with each other coming to a thermal equilibrium
- describe temperature with reference to the average kinetic energy of the atoms and molecules within a system
- investigate and apply theoretically and practically the First Law of Thermodynamics to simple situations: $Q = U + W$
- explain internal energy as the energy associated with random disordered motion of molecules
- distinguish between conduction, convection and radiation with reference to heat transfers within and between systems
- investigate and analyse theoretically and practically the energy required to:
  - raise the temperature of a substance: $Q = mc\Delta T$
  - change the state of a substance: $Q = mL$
- explain why cooling results from evaporation using a simple kinetic energy model.

Image: yucelyilmaz/Shutterstock.com

2A WHAT IS TEMPERATURE?

Temperature is a concept we are familiar with in our everyday lives, but what is the physical difference between a hot object and a cold object? This lesson will establish the kinetic theory of matter, which is a foundation of thermodynamics (the study of heat flow and its effects), and use this theory to explain what temperature really is.

2A What is temperature?	2B How does thermal energy move?	2C How heat affects temperature	2D The Zeroth and First Laws of Thermodynamics

Study design dot points

- convert temperature between degrees Celsius and kelvin
- describe temperature with reference to the average kinetic energy of the atoms and molecules within a system
- explain internal energy as the energy associated with random disordered motion of molecules

Key knowledge units

The kinetic theory of matter	1.1.5.1
Temperature	1.1.1.1 & 1.1.3.1

No previous or new formulas for this lesson

Definitions for this lesson

energy a quantity describing the ability to cause a physical change (scalar)

internal energy the total energy associated with the random motion of particles and the interactions between the particles within a system

kinetic energy the energy associated with the motion of an object

particle a small, discrete object or portion of matter

potential energy the energy associated with the position of an object in the presence of a force that could move the object

state of matter the physical property of an object being either a solid, liquid, or a gas

system a collection of interacting particles or objects that are treated as a single entity

temperature a measure of the average translational kinetic energy of the particles in a system (scalar)

thermal energy see "internal energy"

thermal equilibrium the state of two (or more) systems having the same temperature so that there is no net flow of thermal energy from one system to the other

The kinetic theory of matter 1.1.5.1

OVERVIEW

The kinetic theory of matter states that all matter consists of very small particles that are in constant motion. The small-scale behaviour of these particles can explain the large-scale behaviour of solids, liquids, and gases. Internal energy is the energy associated with the random disordered motion of particles and the interactions between them.

THEORY DETAILS

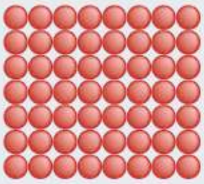
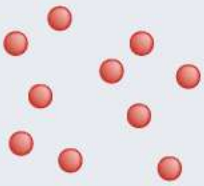
States of matter

When ice melts into water, it takes on very different physical properties such as the ability to flow and change its shape. The kinetic theory of matter provides an explanation for this observation, as well as many other processes that we will encounter within this Area of Study.

We usually model objects as continuous – meaning that we treat them as a single entity. We do this because objects, such as a single football, look and feel as though they are not made of smaller parts. However, the **kinetic theory of matter**:

- states that matter is made of small particles (atoms) which can group to form larger particles (molecules) and lattices.
  - These particles are in a constant state of **random disordered motion**.
- explains how matter exists in different states, as shown in Table 1.

Table 1 The relationship between the arrangement/motion of the particles in each state of matter and the macroscopic properties of each state

State of matter	Particle diagram	Particle arrangement	Particle motion	Properties of object	Example
Solid		• Stuck close together • Regular pattern	• Vibrate about a fixed point • No overall movement	• Fixed volume • Fixed shape	Ice  Image: Valentyn Volkov/ Shutterstock.com
Liquid		• Close together • Random arrangement	• Free to move around each other • Random collisions	• Fixed volume • Shape can change to fit container	Water  Image: Cozine/ Shutterstock.com
Gas		• Far apart • Random arrangement	• Free to move at high speed • Random collisions	• Volume and shape can change to fill a container	Steam  Image: naibank/ Shutterstock.com

Internal energy

In physics, a system is a collection of interacting particles or objects that are treated as a single entity. Internal energy, U, describes the energy of a system associated with both the random disordered motion and the interactions between its particles. For our study of thermodynamics, we use the terms "internal energy" and "thermal energy" interchangeably. We can consider the internal energy of a system to consist of two types of energy:

- Kinetic energy (KE) due to the random disordered motion of all the particles in the system
- Potential energy (PE) due to the interactions between the particles in the system

The SI unit for all types of energy is the joule (J).

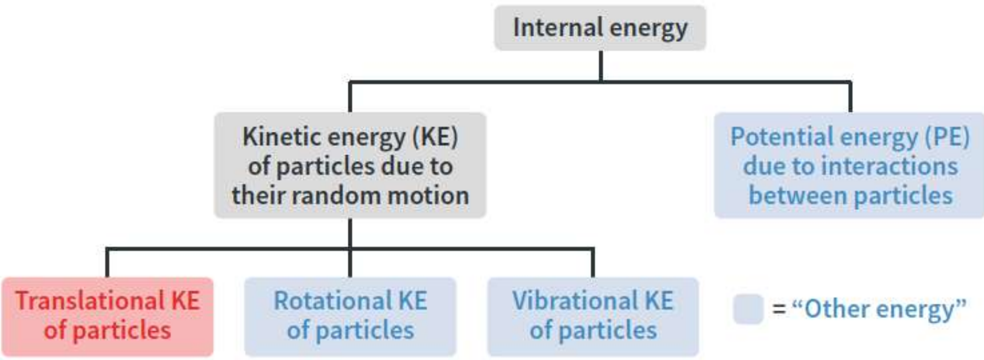


Figure 1 The types of energy that contribute to the internal energy of a system

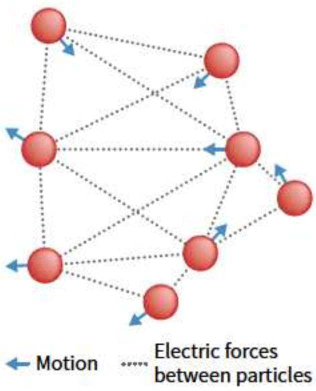


Figure 2 A representation of the random disordered motion of a system of particles and the electric forces acting between the particles

Kinetic energy is the energy of motion. A car has greater kinetic energy when it is driving faster than when it is driving slower. Similarly, a system of particles has greater internal kinetic energy when the particles are moving faster compared to when they are moving slower. This kinetic energy can be further divided into various forms according to the different types of motion of the particles: translational motion of particles, rotational motion of particles, and vibrational motion within the particles. The translational kinetic energy is of particular interest because it relates to the temperature, which will be explained later in the lesson.

Potential energy is the energy stored due to the position of an object and the existence of a force which could move the object. For example, a spring stores potential energy when stretched or compressed because there is a force that acts to return the spring to its original length. Similarly, particles in a system store potential energy due to their positions because there are electrical forces that act between the particles.

The "energy container" model

All systems have some amount of internal (thermal) energy. We can imagine that every system has an "energy container" that stores the internal energy. The "energy container" can be divided into two portions:

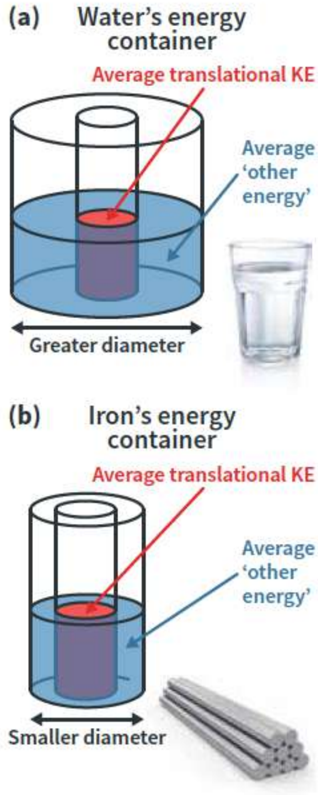
- an average translational kinetic energy portion (the red portion of the containers in Figure 3);
- an average "other energy" portion (the blue portion of the containers in Figure 3), which consists of potential energy, rotational kinetic energy, and vibrational kinetic energy.

The proportion of the internal energy that takes the form of "other energy" is different for different substances (due to differences in the particle structure) as shown in Figure 3.

- Water stores a lot of its internal energy as "other energy". This is represented by the large diameter of the blue "other energy" container in Figure 3(a).
- Iron stores a smaller proportion of its internal energy as "other energy" compared to water. This is represented by the smaller diameter of the blue "other energy" container in Figure 3(b) compared to the diameter of the "other energy" container in Figure 3(a).

There are some points to note regarding this model, which will be helpful throughout this chapter.

- The fill-height of the average translational kinetic energy portion and the average "other energy" portion must be the same for a given substance.
- All substances are modelled as having the same diameter for the average translational kinetic energy portion of the container.
- The fill-height represents the average translational kinetic energy.



Images (top to bottom): Tarasyuk Igor/Shutterstock.com, Salamahin/Shutterstock.com

Figure 3 We can imagine that internal energy is stored in a container for each system. This diagram represents the internal energies for systems made of **(a)** water and **(b)** iron.

Temperature 1.1.1.1 & 1.1.3.1

OVERVIEW

Temperature is a measure of the average translational kinetic energy of the particles within an object. The Kelvin scale is an absolute scale – this means that a zero on the Kelvin scale represents the lowest physical temperature possible.

THEORY DETAILS

Temperature is a measure of the average translational kinetic energy of the random disordered motion of the particles in a system. Note that the vibration of particles in solids (as opposed to vibrations within particles) contributes to this translational kinetic energy. As the temperature of a system increases, its atoms and molecules move faster. These particles also move further apart (which is associated with an increase in potential energy), so the substance expands.

The fill-height of the "energy container" model (which represents the average translational kinetic energy) also represents the temperature of a system, as shown in Figure 4. We can see that there is such a thing as a lowest possible temperature, which describes the state of a system when its particles have the lowest possible kinetic energy (corresponding to the container being empty).

> **USEFUL TIP**
>
> It is important to recognise that temperature measures the average translational kinetic energy because, at any instant in time, the particles within a system will have a range of speeds and hence a range of kinetic energies.

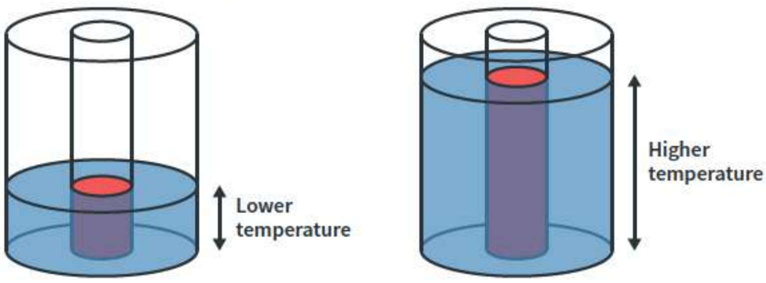


Figure 4 The fill-height, which represents the average translational kinetic energy, also represents the temperature.

When two systems are at the same temperature – meaning that their particles have the same average translational kinetic energy – they are in thermal equilibrium.

Units for measuring temperature

Degrees Celsius (°C) is the common unit used for everyday temperature measurements in most countries, including Australia. However, kelvin (K) is the SI unit for temperature measurements.

USEFUL TIP

When stating a temperature measurement using SI units, we do not include the word "degrees". A measurement of 50 K is stated as "fifty kelvin" (rather than "fifty degrees kelvin").

The Kelvin scale defines the lowest possible temperature as 0 K. This is known as absolute zero. The coldest known place in the Universe is the Boomerang Nebula, which has a temperature of 1 K.

The Celsius scale is based on the freezing point and boiling point of water (at standard atmospheric pressure): the freezing point is set at 0°C and the boiling point is set at 100°C. If the air temperature is 0°C, it means the average translational kinetic energy of the air particles is the same as that of freezing water. Using this scale, the lowest possible temperature is –273.15°C.

The size of one kelvin is the same as the size of one degree Celsius. That is, a temperature increase of 1 K is the same as an increase of 1°C. See Figure 5.

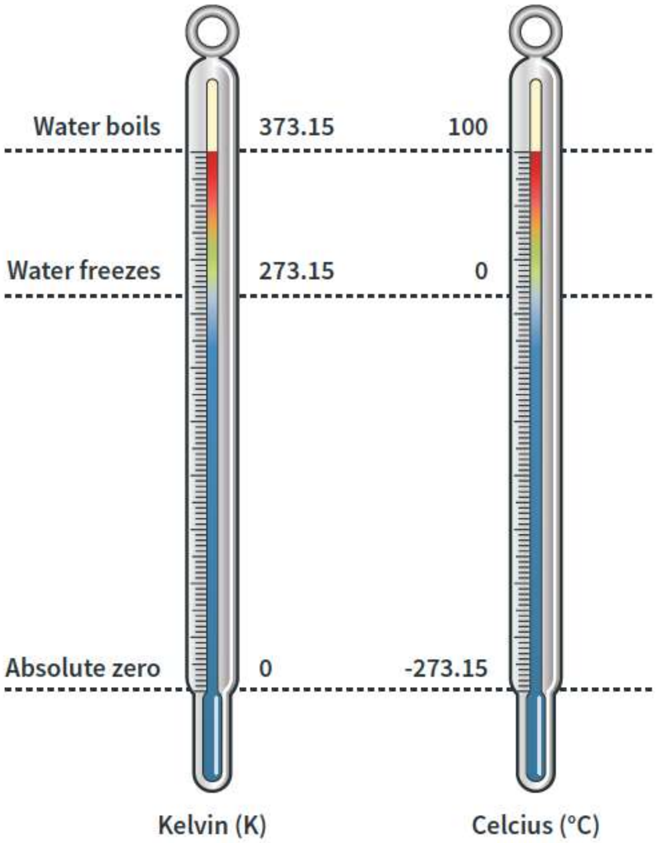


Image: Fouad A. Saad/Shutterstock.com

Figure 5 The Kelvin and Celsius scales. An increment of 1 K is the same as an increment of 1°C, but zero is defined differently for each scale.

- To convert from degrees Celsius to kelvin, add 273.15.
- To convert from kelvin to degrees Celsius, subtract 273.15.

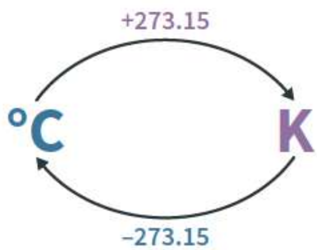
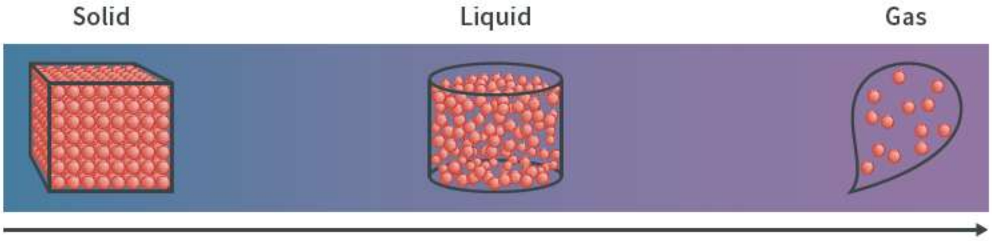


Figure 6 Converting temperature measurements from degrees Celsius to kelvin and vice versa

Theory summary

- The kinetic theory of matter states that all matter consists of particles (molecules or individual atoms) that are constantly moving in a random and disordered way.
- Internal energy describes the energy associated with the motion and interactions between the particles that make up a system. This is also known as thermal energy.



Motion and separation of particles in a given system (internal energy)

	Solid	Liquid	Gas
Shape	Fixed	Not fixed	Not fixed
Volume	Fixed	Fixed	Not fixed

- Internal energy consists of various types of kinetic energy and potential energy.
  - The proportion of each type depends on the substance.
- Temperature is a measure of the **average translational kinetic energy** of the particles in a system.
  - As temperature increases, the particles move faster and further apart.
- Two systems are in thermal equilibrium when they have the same temperature.
- The SI unit for temperature is the kelvin (K). Temperature is also commonly measured in degrees Celsius (°C).
  - The lowest possible temperature is 0 K (–273.15°C).
  - An increase in temperature of 1 K corresponds to an increase of 1°C.

KEEN TO INVESTIGATE?

PhET 'States of Matter' simulation
phet.colorado.edu/en/simulation/states-of-matter

YouTube video: Reactions – How Do We Tell Temperature?
youtu.be/ibmubP26R9M

YouTube video: The Science Asylum – What EXACTLY is Temperature?!
youtu.be/2xalQjmE5VI

The Concord Consortium
lab.concord.org/embeddable.html#interactives/sam/phase-change/5-interatomic-interactions-and-states.json

CONCEPT DISCUSSION QUESTION

If you pour milk into a very hot cup of tea, the milk will quickly diffuse (mix) throughout the tea. If you pour milk into a cold cup of tea, the milk will not diffuse as quickly. Discuss the reason for this difference.

Answers on page 504

Hints
What do you think causes a substance to diffuse (mix) throughout another substance?
What is the relationship between the temperature of a system and the motion of its particles?
How could this behaviour affect the rate of diffusion?

2A Questions

THEORY REVIEW QUESTIONS

Question 1

If a patch of sand at the beach is at a higher temperature than the sea water, we can conclude that the __________ (average/total) __________ (internal/translational kinetic/potential) energy of the particles that make up the sand is greater than that of the molecules that make up the water.

Question 2

a Which of the following best describes internal energy?

- **A** The energy associated with the random disordered motion of atoms and molecules
- **B** The energy associated with the temperature of each atom and molecule

b Which of the following best describes the type(s) of energy that make up internal energy?

- **A** The energy due to the overall movement of the system
- **B** Kinetic energy of atoms/molecules and potential energy due to interactions between atoms/molecules

Question 3

A given system has the greatest internal energy when it is a __________ (solid/liquid/gas). Its particles have the __________ (greatest/least) freedom to move in this state.

The system has the least internal energy when it is a __________ (solid/liquid/gas). Its particles have the __________ (greatest/least) freedom to move in this state.

Question 4

The atoms and molecules in __________ objects are constantly moving.

- **A** very hot
- **B** all

Question 5

The lowest possible temperature is __________ K, which is equivalent to __________°C.

- **A** 0, –273.15
- **B** –273.15, 0

Question 6

A change in temperature, ΔT, of 200°C is equivalent to:

- **A** (200 – 273.15) K
- **B** (200 + 273.15) K
- **C** 200 K

DECONSTRUCTED EXAM-STYLE QUESTION

Question 7 (3 MARKS)

A physics teacher is holding a hot cup of coffee in her hand as she marks exams. She is so busy marking the exams that she forgets to drink the coffee and, eventually, the cup of coffee reaches thermal equilibrium with her hand.

Prompts

a What is temperature a measure of?

- **A** How hot each particle in a system is
- **B** The total kinetic energy of a system
- **C** The internal energy of a system
- **D** The average translational kinetic energy of the particles in a system

b What does it mean for the teacher's hand to be in thermal equilibrium with the cup of coffee?

- **A** There is no force between the hand and the cup of coffee.
- **B** The hand and the cup of coffee are at the same temperature.
- **C** The particles in the hand and the cup of coffee have stopped moving.
- **D** The temperatures of the hand and the cup of coffee add to zero.

Question

c Describe how the average translational kinetic energy of the particles in the teacher's hand compares with the average translational kinetic energy of the particles in the cup of coffee throughout the process of reaching thermal equilibrium. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 8 (2 MARKS)

Is it possible to increase the temperature of a system while keeping the internal energy constant? Justify your answer.

Hint: use the "energy container" model to help you.

Question 9 (1 MARK)

The surface of the planet Venus maintains a nearly constant temperature of 735 K. The temperature does not decrease during the night because of its thick atmosphere. Convert the temperature of the surface of Venus to degrees Celsius.

Question 10 (2 MARKS)

The surface of the planet Mercury can reach temperatures as high as 450°C during the day, and as low as –170°C at night. This large variation occurs because Mercury does not have an atmosphere to trap the thermal energy during the night.

a Convert the minimum nighttime temperature on Mercury to kelvin. (1 MARK)

b Calculate the temperature range (the difference between the maximum and minimum temperatures) of the surface of Mercury. Provide your answer in kelvin. (1 MARK)

Question 11 (2 MARKS)

The planet Mars' surface reaches a maximum temperature of 20°C during the day and a minimum of –125°C during the night. Compare the average translational kinetic energy of the atoms and molecules on the surface of Mars during the day with their average translational kinetic energy during the night. Justify your answer.

Question 12 (2 MARKS)

With reference to the relationship between macroscopic (large-scale) physical properties and molecular motion, explain why it is easy to pour water into a bottle and fill it up but it is not easy to do this with ice.

Question 13 (3 MARKS)

After reading about the relationship between temperature and energy, Archie states that a fast-moving basketball must have a higher temperature than a stationary basketball. Evaluate Archie's statement. Justify your response.

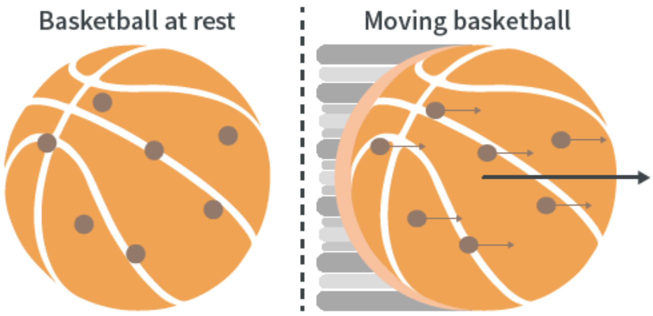


Image: vectoric/Shutterstock.com

Question 14 (2 MARKS)

A backyard pool and an Olympic swimming pool (which is much larger than the backyard pool) are both at a temperature of 26°C.

a Compare the internal energy of the water in the backyard pool with the internal energy of the water in the Olympic pool. (1 MARK)

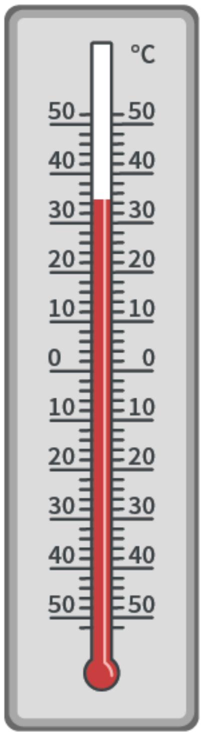
b Compare the average translational kinetic energy of the water molecules in the backyard pool with the average translational kinetic energy of the molecules in the Olympic pool. (1 MARK)

Key science skills

Question 15 (6 MARKS)

A class conducts an experiment in which a beaker of oil is heated and the temperature is measured each minute.

a What is the absolute uncertainty of the thermometer shown? (1 MARK)



b The data collected is shown in the table.

Time (mins)	0	1	2	3	4
Temp (°C)	15	23	30	38	44

Graph the data on a set of axes. Include:

- an appropriate scale, labels, and units for each axis.
- uncertainty bars for the temperature.
- a line of best fit.

(5 MARKS)

2B HOW DOES THERMAL ENERGY MOVE?

In the previous lesson, we learned about temperature and internal energy. But how does the energy associated with temperature get from one place to another? And how does this explain why metal feels so cold on a chilly day? To answer these questions, this lesson will introduce us to heat as a physical quantity, and we will explore the three types of heat transfer.

2A What is temperature?	2B How does thermal energy move?	2C How heat affects temperature	2D The Zeroth and First Laws of Thermodynamics

Study design dot point

- distinguish between conduction, convection and radiation with reference to heat transfers within and between systems

Key knowledge units

Heat	1.1.6.1
Conduction	1.1.6.2
Convection	1.1.6.3
Thermal radiation	1.1.6.4

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$\frac{Q}{t} \propto \Delta T$ heat flow rate for conduction

Definitions for this lesson

convection the transfer of heat through the bulk movement of matter

convection cell a circular flow of fluid caused by differences in temperature and hence fluid densities

density mass per unit volume; a measure of how closely packed matter is

electromagnetic radiation a disturbance in the electric and magnetic fields (electromagnetic fields) of charged particles; includes visible light

fluid a substance that flows easily; a liquid or gas

heat energy that is flowing between systems due to a difference in temperature

medium the physical substance through which energy (e.g. heat or sound) travels

thermal conduction the transfer of heat through direct contact

thermal radiation the transfer of heat in the form of electromagnetic radiation

vacuum a region that does not contain matter

Heat 1.1.6.1

OVERVIEW

Heat is thermal energy that transfers from one system to another system. Two systems at the same temperature are in thermal equilibrium, which means there will be no net transfer of heat between them.

THEORY DETAILS

Heat, Q, is thermal energy that is flowing from one system to another, increasing one system's internal energy by the same amount that the other system's decreases. The flow of thermal energy between systems is called **heat transfer**.

- Heat is measured in joules (J) since it is energy.
- Two objects that are exchanging heat with each other are in thermal contact.
- Heat is not temperature.
- Heat is not a property of a single object or system.

For two systems in thermal contact, there is a net flow of heat from the hotter (higher temperature) system to the colder (lower temperature) system.

- The transfer is faster when the difference in temperature between the systems is greater.
- Surface area and molecular structure/composition of the substances/materials also affect the heat transfer rate.

Eventually, the two systems reach the same temperature. This is known as **thermal equilibrium**. There is no net heat transfer between systems in thermal equilibrium.

Using the energy container model from Lesson 2A, heat is energy that flows between containers. We can model this flow of energy as liquid flowing through a pipe connecting the containers. The liquid always flows from the container that is filled to a greater height (higher temperature system) to the container with the lower fill-height (lower temperature system).

Figure 1 uses this model to represent a heat transfer from hot iron to cool water.

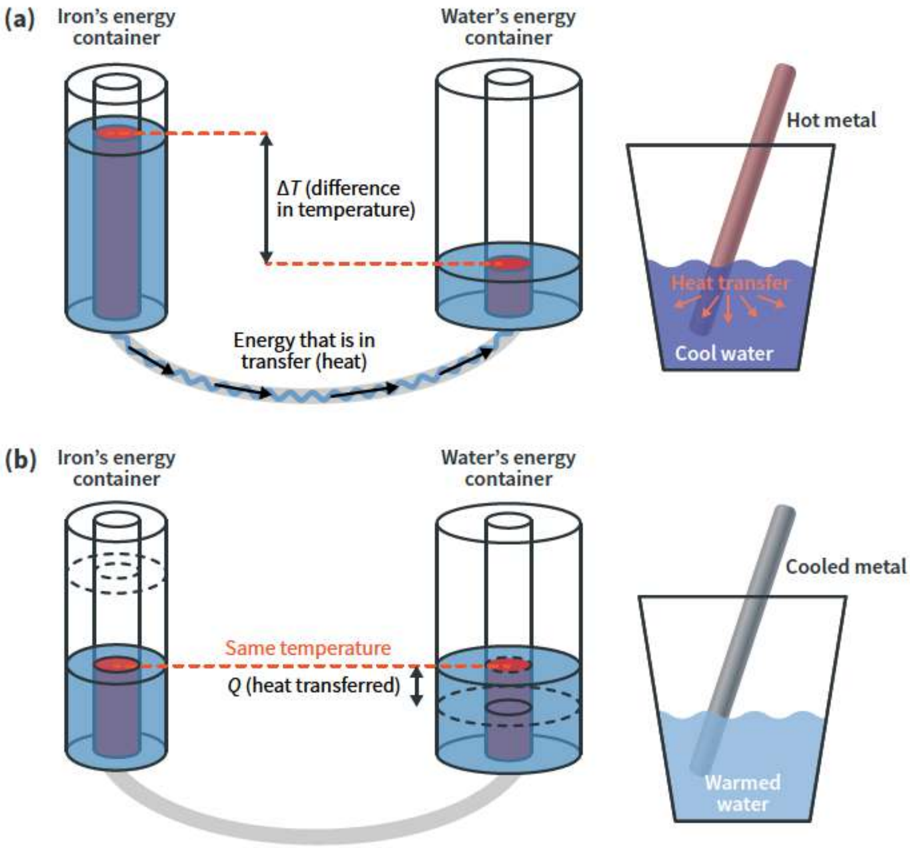


Figure 1 **(a)** Hot iron transferring energy to cool water in a bucket. **(b)** The two systems after thermal equilibrium has been reached.

Conduction 1.1.6.2

OVERVIEW

Conduction is a form of heat transfer between systems that is due to collisions between their particles. The rate of conduction is proportional to the temperature difference between the two systems. It also depends on the materials through which the conduction occurs.

THEORY DETAILS

When we touch an object, we might believe that we are feeling the temperature of the object, but in reality we are feeling the energy transfer between the object and our hands. This is an example of a type of heat transfer called conduction.

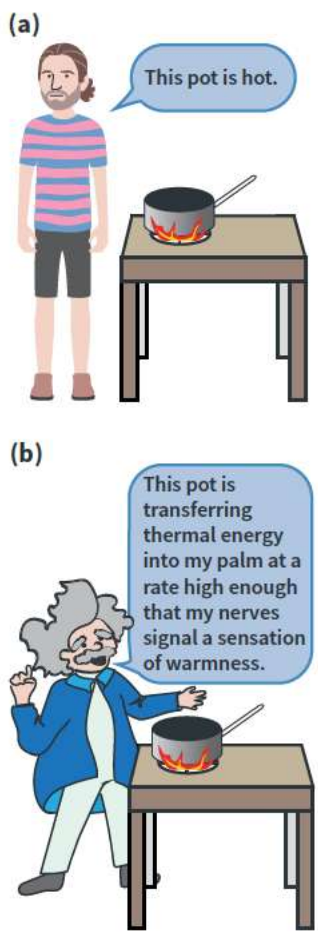


Figure 2 **(a)** The everyday (incorrect) explanation vs the **(b)** scientific explanation for why hot objects feel 'hot'.

Conduction is a heat transfer that can occur for all phases of matter (solids, liquids, and gases). Conduction between two systems only occurs when:

- they are in contact.
- they are at different temperatures. Remember, two systems can be at different temperatures but have the same internal energy (and vice versa).

The heat transfer in Figure 1, with hot iron being cooled down by water, was an example of conduction. Conduction occurred because the metal was in direct contact with the water, and the water was at a lower temperature than the metal.

The heat flow rate (measured in J s^{-1}) between two systems due to conduction is directly proportional to their difference in temperature.

$$\frac{Q}{t} \propto \Delta T$$

Q = net heat transferred (J), t = time taken for transfer (s), ΔT = magnitude of difference in temperature between the two systems (K or °C)

This means the factor by which the heat flow rate, $\frac{Q}{t}$, changes is equal to the factor by which ΔT changes. For example, if the difference in temperature between two objects halves, the heat flow rate will also halve.

Worked example 1

Initially, the iron in Figure 1 transfers 360 J to the water every 0.500 seconds. The water is at a temperature of 20°C, while the iron is at 820°C.

a Calculate the initial heat flow rate between the metal and the water, $\frac{Q}{t}$.

b After a period of time, the water is at 40°C and the iron is at 120°C. What is the new rate that heat flows?

Working	Process of thinking
a $\frac{Q}{t} = \frac{360}{0.500}$ $\frac{Q}{t} = 720 \text{ J s}^{-1}$	$Q = 360$ J, $t = 0.500$ s The unit for rate of heat transfer will be J s^{-1} since the unit for heat is J.
b $\Delta T_{before} = T_{iron} - T_{water} = 820 - 20 = 800$°C $\Delta T_{after} = T_{iron} - T_{water} = 120 - 40 = 80$°C	We take the smaller temperature from the larger temperature to get the magnitude. Since we are just looking for the difference, we do not need to convert to kelvin.
So ΔT has changed by a factor of $\frac{80}{800} = \frac{1}{10}$.	We arrive at this by dividing the final temperature difference by the initial temperature difference.
$\frac{Q}{t} = \frac{1}{10} \times 720$ $\frac{Q}{t} = 72 \text{ J s}^{-1}$	The factor that $\frac{Q}{t}$ changes by is the factor ΔT changes by, which is $\frac{1}{10}$ in this case.

The rate of conduction also depends on the area of contact through which the conduction occurs – the rate of conduction is greater when this area is greater.

How conduction works

As we learned in Lesson 2A, temperature is a representation of the average translational kinetic energy of particles in a system. When two systems are in physical contact, particles at their boundaries collide and exchange translational kinetic energy.

- The higher temperature system's particles will, on average, have greater translational kinetic energy than the particles in the lower temperature system.
- In each collision, translational kinetic energy is usually transferred from the particle with more translational kinetic energy to the particle with less translational kinetic energy (Figure 3).

- Hence, overall, energy transfers from the higher temperature system to the lower temperature system over time.

Since particles that make up systems also collide with each other, conduction also occurs within systems.

Image: Gencho Petkov/Shutterstock.com

Figure 3 Translational kinetic energy tends to spread out among particles, like in the opening 'break' shot in a game of pool.

Thermal conductors and insulators

Due to their differing atomic and molecular structures, some materials and substances will be better at conduction than others are.

- Something that is good at conducting heat is called a good thermal conductor.
- Something that is bad at conducting heat is called a good thermal insulator.

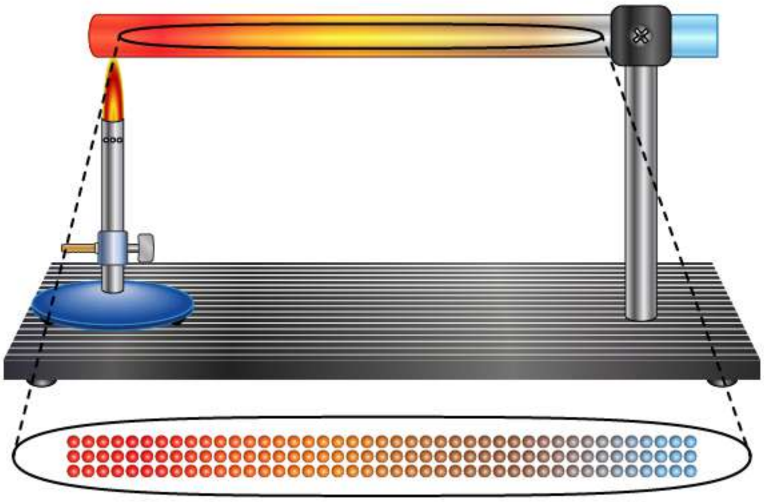


Image: Fouad A. Saad/Shutterstock.com

Figure 4 Conduction occurring within a metal rod when the left side is heated. The atoms on the left transfer energy to the atoms on the right through collisions.

A good thermal conductor will transfer heat faster both within itself and to other systems. Pure metals are good conductors because the atoms are close together and they have free-moving electrons. This is why metals feel very cold on cold days and very hot on hot days: they transfer heat rapidly to or from our skin.

The opposite is true for thermal insulators: they transfer heat slowly. Air is an example of a good insulator. Its particles are spaced out and do not collide very often, so the rate that heat is transferred is very slow. A vacuum is the ideal insulator since there are no particles available to have collisions.

Table 1 Examples of good thermal conductors and insulators

Good thermal conductors	Good thermal insulators
Gold	Wood
Copper	Air
Steel	Most plastics
Graphite	Feathers (largely because they trap air)
Diamond (best known thermal conductor)	Wool (largely because it traps air)

Convection 1.1.6.3

OVERVIEW

Convection is a form of heat transfer within a fluid that is due to the overall movement of matter between hotter regions and colder regions. Natural convection (as opposed to forced convection) occurs when the matter moves from regions of high density to low density, which are a result of different temperatures within the fluid.

THEORY DETAILS

Convection is the transfer of heat through the macroscopic movement of matter between areas of different temperature. Since the matter has its own thermal energy, when matter moves so does its thermal energy.

- Convection only occurs in fluids (substances that flow).
- Convection can be natural or forced.

Natural convection

According to the kinetic theory of matter, a higher temperature means that particles have greater average translational kinetic energy. This additional translational kinetic energy means that particles at higher temperatures take up more space, decreasing the density of the material. Fluid with higher density sinks and displaces the less dense fluid, pushing the less dense fluid upwards.

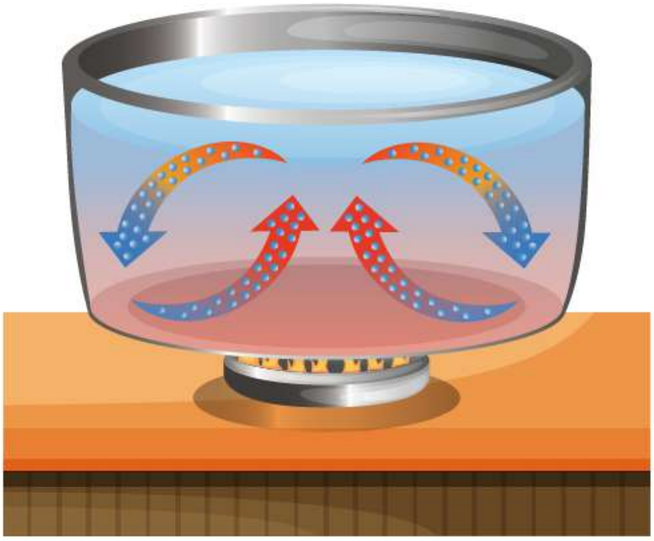


Image: BlueRingMedia/Shutterstock.com

Figure 5 Water particles in a pot that is heated at its base. The arrows represent convection cells.

Figure 5 shows natural convection where a fluid is constantly heated from the bottom.

- The colder fluid is denser, so sinks and pushes up the hotter fluid.
- Therefore energy is convected away from the heating area.
- The fluid cools down as it rises by transferring heat to its cooler surroundings, increasing in density and falling back down to the bottom.
- If the heating persists, particles continue rising and falling in what we call convection cells.

Convection cells are circular flows of fluid caused by ongoing convection. The formation of convection cells explains why indoor heaters are often located close to the floor. As shown in Figure 6, hot air rises from the heater (while drawing in cooler air), cools across the top of the room, falls, and is drawn back to the heater. In this way, thermal energy from the heater is transferred around the room.

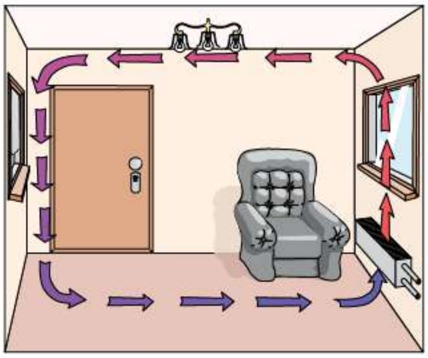


Image: Sergey Merkulov/Shutterstock.com

Figure 6 A convection cell formed by a heater.

Forced convection

Forced convection is any fluid flow that leads to a transfer of thermal energy where the heating itself does not drive the flow; another energy source must drive the flow such as a fan blowing air or a spoon mixing a cup of tea.

Forced convection can transfer heat from anywhere in the fluid, not just from the bottom. For example, if a heater was placed at the top of a room, a built-in fan could convect heat away by blowing hot air downwards. Figure 7 illustrates this process.

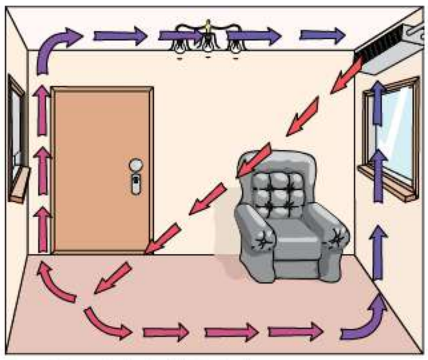


Image: Sergey Merkulov/Shutterstock.com

Figure 7 Forced convection by a heater with a fan can heat a room from above.

Thermal radiation 1.1.6.4

OVERVIEW

Thermal radiation is a form of heat transfer that is due to the emission and absorption of energy as electromagnetic radiation. Matter is not required between the emitting and absorbing substances.

THEORY DETAILS

The last type of heat transfer is thermal radiation, which is emitted by all objects with a temperature above absolute zero (0 K). Radiation is the heat transfer responsible for the warmth we feel from the Sun.

Charged particles emit electromagnetic radiation whenever they accelerate. When the charged particles inside atoms (protons and electrons) accelerate while vibrating or colliding (due to the random motion associated with thermal energy), some of their translational kinetic energy is transformed into electromagnetic radiation. This causes a decrease in the temperature of the emitting substance.

Electromagnetic radiation describes energy-carrying variations in electric and magnetic fields.

- It travels away from the source at the speed of light.
- It does not require a medium (which means it can travel through a vacuum).

The way charged particles emit radiation can be considered to be similar to the way that balls produce sound when colliding with objects, as shown in Figure 9. The ball emits sound when it collides, and the 'loudness' is dependent on the kinetic energy of the ball. In the same way, charged particles emit radiation when they accelerate due to vibrations or collisions. They lose more energy by emitting radiation when they have more translational kinetic energy to begin with (i.e. when an object is hotter).

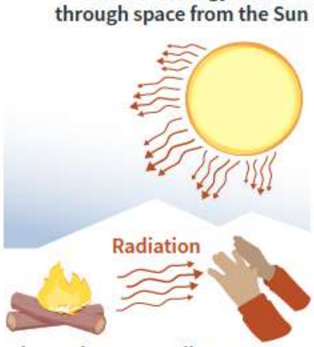


Figure 8 Thermal energy can be transferred to us through both the air and the vacuum of space.

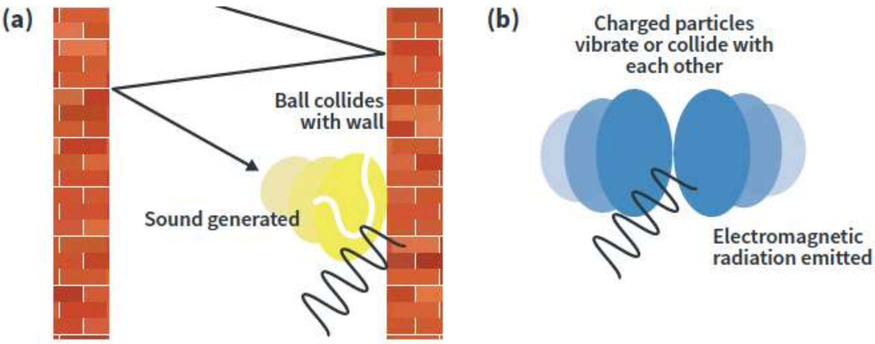


Figure 9 **(a)** A ball bouncing between two walls mimics how **(b)** charged particles accelerate.

When radiation meets an object or substance, it is transmitted, reflected, and/or absorbed (see Figure 10).

- Transmission means the radiation continues through the object.
- Reflection means the radiation bounces off the object and continues to travel in a different direction.
- Absorption means the particles in the object receive the energy from the radiation.
  - The particle's energy increases, equal to the energy of the absorbed radiation, and the temperature of the object increases.
  - The radiation ends its journey, completing the heat transfer.

The percentage of radiation that is transmitted, reflected, and absorbed by an object depends on the material of the object. This will be covered in further detail in Lesson 3B.

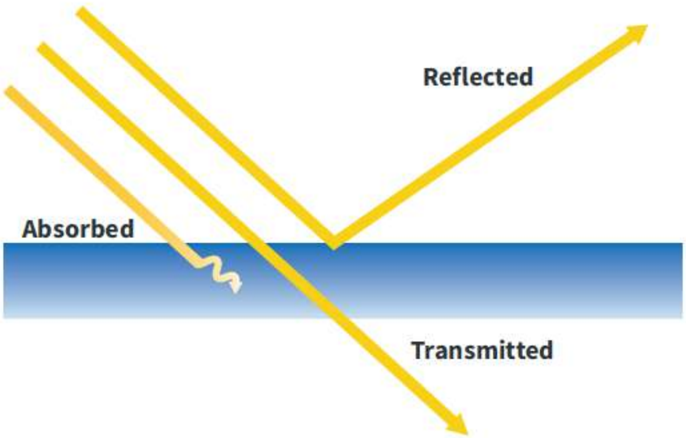


Image: OSweetNature/Shutterstock.com

Figure 10 Absorption, transmission, and reflection of electromagnetic waves

Theory summary

- Heat is thermal energy that transfers between two systems, decreasing the internal energy of one system and increasing the internal energy of the other by the same amount.
  - Objects at the same temperature are said to be in **thermal equilibrium** and do not have a net flow of heat.
- Heat transfers take three different forms:

	In what situations it occurs	What it is	Medium required?	Matter transferred?	Energy transferred?
Conduction	Occurs: • when two systems are physically touching. • within systems.	Particles collide with each other across the contact surface or within the system, transferring their thermal energy.	✓	×	✓
Convection	Occurs in fluids.	Particles move around the fluid, carrying their energy with them.	✓	✓	✓
Radiation	Occurs in all systems, but is more significant for hotter objects.	Charged particles transform thermal energy into electromagnetic radiation (thermal radiation) as they accelerate.	×	×	✓

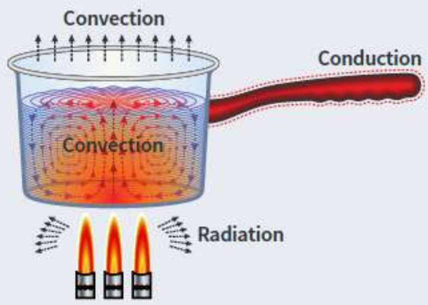


Image: Fouad A. Saad/Shutterstock.com

- The heat transfer rate for conduction is related to the difference in temperature: $\frac{Q}{t} \propto \Delta T$.
- Convection cells form due to convection and represent the path fluid takes.
- For a given fluid, the colder fluid is denser than the hotter fluid, so the colder fluid sinks and the hotter fluid rises.
- Radiation can be transmitted, reflected, and/or absorbed when interacting with matter.

KEEN TO INVESTIGATE?

PhET 'Energy Forms and Changes' simulation
phet.colorado.edu/en/simulation/energy-forms-and-changes

YouTube video: Veritasium – Misconceptions About Temperature
youtu.be/vqDbMEdLiCs

YouTube video: expertmathstutor – Physics – Heat Transfer – Conduction
youtu.be/9joLYfayee8

The Concord Consortium Energy 2D simulation
energy.concord.org/energy2d/

CONCEPT DISCUSSION QUESTION

Electromagnetic radiation from the Sun travels through the vacuum of space, before travelling through our atmosphere.

Discuss how energy from the Sun could, after travelling to Earth via radiation, later undergo conduction and convection (in either order)?

Answers on page 504


Image: Luciano Cosmo/Shutterstock.com

Hints
What kinds of substances on Earth undergo convection?
What happens to a particle after it absorbs energy? How does this differ between solids, liquids, and gases?

2B Questions

THEORY REVIEW QUESTIONS

Question 1

Heat is flowing from System A to System B. Which of the following statements is **false**?

A System B is gaining internal energy.

B The two systems are in thermal equilibrium.

C Energy is flowing between the systems.

D System B is colder than System A.

Question 2

Copy the table and for each type of heat transfer, tick the appropriate descriptions.

	Relies on particle vibrations or collisions	Matter travels with the heat	Works well through air
Conduction			
Convection			
Thermal radiation			

Question 3

Fill in the gaps in the following paragraph to describe the process of conduction.

When two systems at different __________ (temperatures/internal energies) are __________ (separated/in contact), __________ (cold/heat) flows from one system to the other due to conduction. This means that the __________ (heat/internal energy) of each system is changing.

Question 4

Selina's hand is at a temperature of 30°C when she touches a ball.

a Choose a temperature at which the ball will feel cold to Selina.

A 35°C

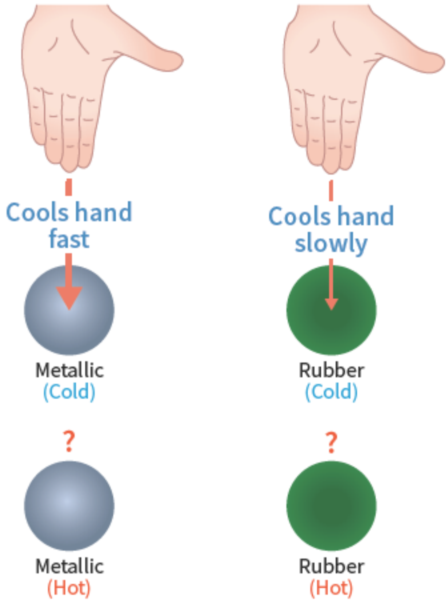
B 30°C

C 25°C

b Selina realises that a cold rubber ball cools her hand slower than a cold metallic ball (at the same temperature as the rubber ball). When the metallic and rubber balls are both hotter than her hand (at the same temperature as each other), which would heat her hand at a greater rate?

A The metallic ball

B The rubber ball



Question 5

Fill in the gaps in the following paragraph to describe why you will usually feel warmer under a blanket.

We feel warmer under a blanket, compared to without a blanket, because the amount of __________ (heat/coldness/energy) our body has decreases at a smaller rate. The amount of __________ (heat/coldness) that flows from our bodies to the colder surroundings is reduced because blankets are good __________ (conductors/insulators/radiators).

Use the following information to answer Questions 6–9.

Kaya conducts four experiments to compare the effects of different types of heat transfer.

- In Experiment 1, she heats water at the bottom of a test tube and measures the temperature of the water at the top of the tube.
- In Experiment 2, she heats water at the top of a test tube and measures the temperature of the water at the bottom of the tube.
- In Experiment 3, she heats the bottom of a piece of steel and measures the temperature of the top of the steel.
- In Experiment 4, she heats the top of a piece of steel and measures the temperature of the bottom of the steel.

In each experiment, the water/steel is initially at room temperature.

Experiment 1

Experiment 2

Experiment 3

Experiment 4

Images: DesignPrax/Shutterstock.com

Kaya recorded her observations after one minute of heating for Experiments 1–3 in a table, as shown.

	Observations
Experiment 1	Significant increase in temperature.
Experiment 2	No significant change in temperature.
Experiment 3	Significant increase in temperature.
Experiment 4	

Question 6

The type of heat transfer that is most responsible for the water at the top of the tube's temperature increasing Experiment 1 is

A conduction.

B convection.

C radiation.

Question 7

The best explanation for the different results between Experiment 1 and 2 is that

A heat always rises.

B hot fluids tend to rise and cold fluids tend to sink due to different densities.

Question 8

The type of heat transfer that is most responsible for the steel at the top's temperature increasing in Experiment 3 is

A conduction.

B convection.

C radiation.

Question 9

What is the most likely observation for Experiment 4?

A "Significant increase in temperature."

B "No significant change in temperature."

Question 10

Use the following diagram to answer parts **a** and **b**.

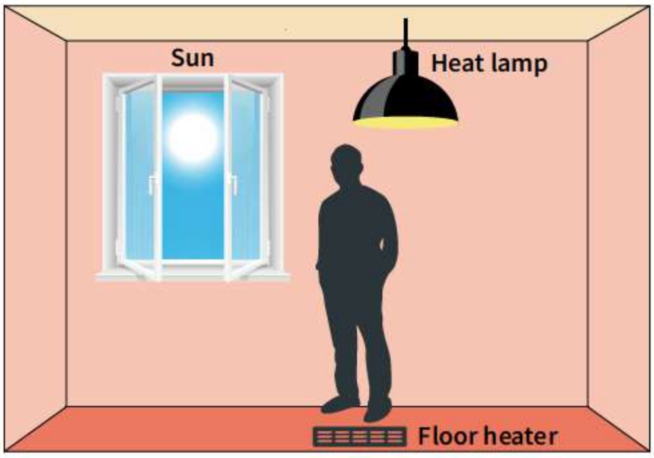


Image: Laurentiu Timplaru, Oewsiri, Alena Nv/Shutterstock.com

a Which heat source transfers heat to the person through convection?

- **A** The heat lamp
- **B** The Sun
- **C** The floor heater (central heating vent)

b Identify the best reason for your answer to part **a**.

- **A** It emits hot collections of air particles, leading to hot air circulating the room.
- **B** Its particles collide with the person, increasing their translational kinetic energy.
- **C** It generates radiation which flows to the person, heating up their skin and the air around them.

Question 11

We generally feel cooler in the shade. Why is this?

A We give off more heat in the shade, and thus cool down quicker.

B We are shielded from the wind, and thus convection, when we stand in the shade.

C Shadows transfer coldness to us.

D Thermal radiation from the Sun does not reach us in the shade.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 12 (3 MARKS)

Thomas and Sabrina are debating whether the fluid in a beaker continuously heated from its top will undergo convection. Thomas says that whenever heat is constantly applied to a fluid, convection cells form. Sabrina says that convection cells will not form due to how the fluid is being heated.

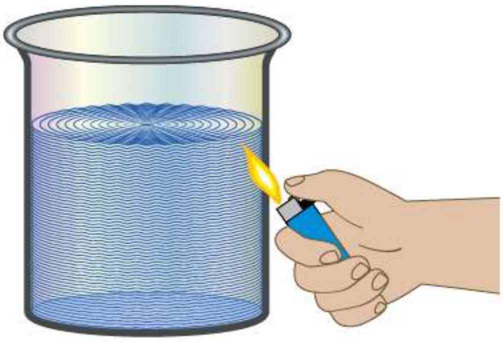


Image: Fouad A. Saad, noname000/Shutterstock.com

Prompts

a Which is the best description of the process of heating by natural convection?

- **A** Thermal energy moves through the contact between hot and cold regions.
- **B** Vibrations of particles cause collisions which spread thermal energy.
- **C** Hot fluids and cold fluids mix evenly and reach thermal equilibrium.
- **D** Colder fluids, which are more dense, sink, and hotter fluids, which are less dense, rise.

b Which direction does heat tend to flow during the process of natural convection?

- **A** Up
- **B** Down
- **C** Left
- **D** Right

Question

c Who is correct? Explain your answer. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 13 (1 MARK)

Which statement best describes thermal conduction?

A A heat transfer that occurs when particles emit radiation by accelerating.

B A heat transfer that occurs when particles exchange energy through collisions.

C A heat transfer that occurs when particles move around a fluid and change the distribution of energy.

Question 14 (1 MARK)

Which statement best describes thermal radiation?

A A heat transfer that occurs when particles emit radiation by colliding.

B A heat transfer that occurs when particles emit radiation by vibrating.

C Both of the above

Question 15 (1 MARK)

A wet bird is losing 100 J of energy every second due to conduction with the air. How much energy would it transfer through conduction every second if the temperature difference between itself and the air increased by a factor of 1.5?

A 200 J **B** 150 J **C** 100 J **D** 50.0 J

Question 16 (1 MARK)

Which of the following (A–D) depicts convection cells?

A

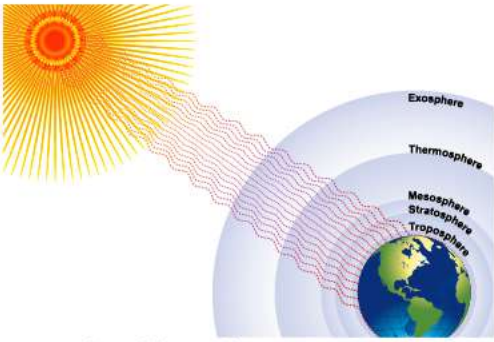


Image: Fouad A. Saad/Shutterstock.com

B

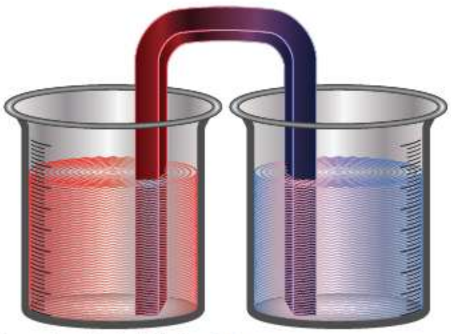


Image: Fouad A. Saad/Shutterstock.com

C

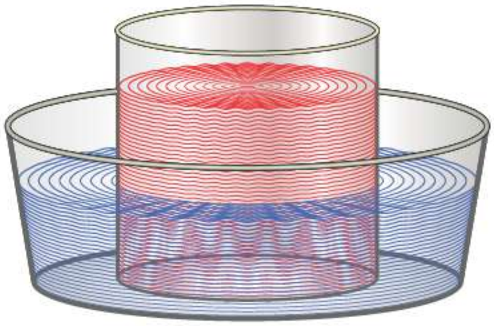


Image: Fouad A. Saad/Shutterstock.com

D

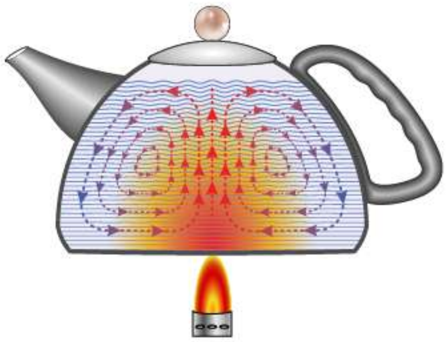


Image: Fouad A. Saad/Shutterstock.com

Question 17 (1 MARK)

Two rubber balls of different sizes in identical surroundings are conducting heat to their surroundings at different rates. Choose the option below that reflects what we can tell about their temperatures.

A The two balls are at equal temperatures.

B The two balls are at different temperatures.

C It is impossible to determine whether they are at equal or different temperatures.

Question 18 (3 MARKS)

Zev is applying an ice pack to his sore head. Explain how the ice pack cools Zev's head down, making sure to identify the heat transfer that is occurring.

Question 19 (2 MARKS)

Skinny Jim is standing by a campfire, as seen in scenario A. Jim wonders whether he would heat up if there was no air between him and the campfire, as seen in scenario B.

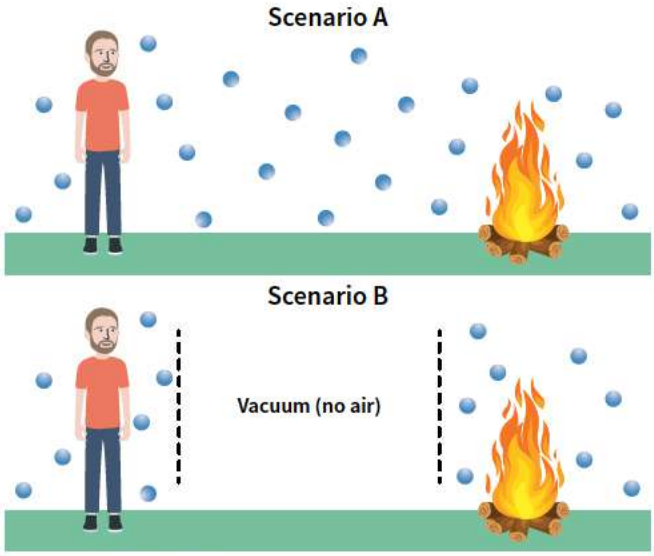


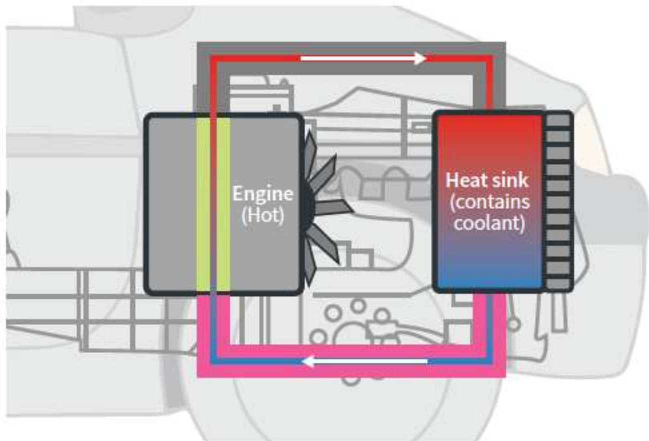
Image: Hanaha/Shutterstock.com

a Will Jim feel the warmth of the campfire in scenario B? (1 MARK)

b Skinny Jim now wants to cook some marshmallows. He notices it is much quicker to cook his marshmallows above the fire than to its side. Identify the heat transfer responsible for this difference. (1 MARK)

Question 20 (3 MARKS)

Car engines cool down by circulating liquid coolant, transferring energy by conduction and convection. The coolant absorbs heat from the engine, and a fan cools down the coolant in a 'heat sink'. The diagram shows a simplification of the cooling system of a car engine.



a The engine piping (green) can be made of aluminium or plastic. Which would be better at transferring heat from the engine to the coolant? (1 MARK)

b Suppose we want to limit the amount of energy transferred between the coolant and its surroundings while it travels to the engine. Should plastic or aluminium be used for this piping (pink)? Justify your answer with relevant theory. (2 MARKS)

Question 21 (2 MARKS)

An oven mitt at 300 K is in direct contact with a hot plate at 340 K, and heat is transferring between them at a rate of 80 J s^{-1}. What difference in temperature would cause the rate to halve to 40 J s^{-1}?

Question 22 (3 MARKS)

A block of rubber and a block of wood have been placed in thermal contact. As a result, the internal energy of the wood has begun to increase. Assume the blocks are not in thermal contact with any other objects.

a Before the two objects were placed in thermal contact, was the rubber hotter or colder than the wood? (1 MARK)

b The two blocks are exchanging heat only through conduction. Use a relevant mathematical relation to explain why there will no longer be a net flow of heat between the blocks once they reach thermal equilibrium. You do not need to refer to the kinetic theory of matter. (2 MARKS)

Question 23 (4 MARKS)

Computers cool down their central processing unit (CPU) by placing 'heat sinks' on them, which absorb heat from the CPU through conduction. An engineer is trying to optimise her computer's cooling by keeping its heat sink cool.

a The heat sink has thin fins that are designed to create a high surface area. Given that this heat sink cools down as a result of thermal conduction with the air, what purpose would this serve? (2 MARKS)

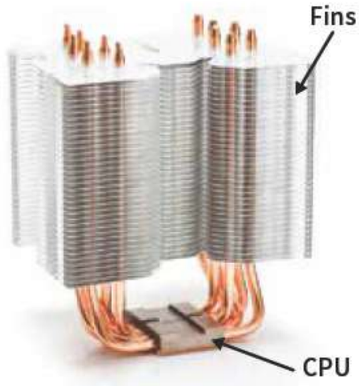


Image: Draw05/Shutterstock.com

b The engineer's computer still overheats, so she looks for a new solution. Inspired by how car engines cool down, she attaches a fan to her heat sink. The CPU no longer overheats. Describe how the heat is moved away from the fins in this setup, making sure to describe the role of the fan. (2 MARKS)

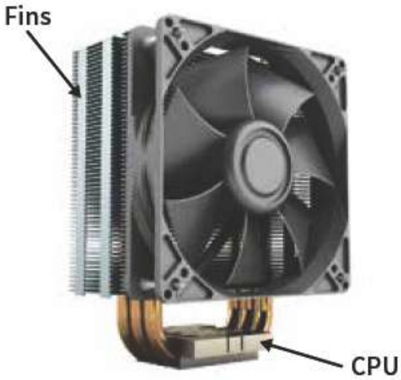


Image: NosorogUA/Shutterstock.com

Previous lessons

Question 24 (2 MARKS)

Describe the difference between the motion of particles in a solid compared with the motion of particles in liquids and gases.

Key science skills

Question 25 (2 MARKS)

A scientist wants to calculate the total rate that heat flows out of a campfire by adding the rates of conduction, convection, and thermal radiation.

	Conduction	Convection	Thermal radiation	Total rate
Heat flow rate (kJ s^{-1})	0.3	5.7	4.502	

a What will be the number of significant figures for the total rate? (1 MARK)

b If the scientist wanted to calculate the total heat, Q, emitted over t = 5.0 seconds with the formula $Q = total\ rate \times t$, how many significant figures would Q have? (1 MARK)

2C HOW HEAT AFFECTS TEMPERATURE

Cooking oil will get hotter on a stove faster than the same quantity of water. A smaller volume of oil will get hotter faster than a larger volume of oil. These observations suggest that the change in temperature of a substance depends on the substance itself as well as the amount of that substance. Water and steam can both exist at 100°C; so where does the energy go when water turns to steam? This lesson will build on the concepts established in Lesson 2A and Lesson 2B to present a quantitative relationship between heat and temperature.

2A What is temperature?	2B How does thermal energy move?	2C How heat affects temperature	2D The Zeroth and First Laws of Thermodynamics

Study design dot points

- investigate and analyse theoretically and practically the energy required to:
  - raise the temperature of a substance: $Q = mc\Delta T$
  - change the state of a substance: $Q = mL$
- explain why cooling results from evaporation using a simple kinetic energy model

Key knowledge units

Specific heat capacity	1.1.7.1
Latent heat	1.1.7.2
Evaporative cooling	1.1.8.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$Q = mc\Delta T$ heat needed to increase temperature
	$Q = mL$ heat needed to change state

Definitions for this lesson

boil convert from liquid to gas at a certain temperature and pressure

condense convert from gas to liquid at a certain temperature and pressure

evaporate convert from liquid to gas only at the liquid's surface due to high-energy particles in the liquid escaping

freeze convert from liquid to solid at a certain temperature and pressure

latent heat the heat absorbed or released to change the state of a substance

melt convert from solid to liquid at a certain temperature and pressure

specific heat capacity the heat per unit of mass needed to increase the temperature of a substance by one kelvin (or degree Celsius)

specific latent heat of fusion the heat per unit of mass needed to convert a given substance from a solid into a liquid

specific latent heat of vaporisation the heat per unit of mass needed to convert a given substance from a liquid into a gas

Specific heat capacity 1.1.7.1

OVERVIEW

All substances have a specific heat capacity, which is a measure of the heat transfer needed to change the temperature of one kilogram of the substance by one kelvin. A substance with a low specific heat capacity changes temperature more easily than a substance with a high specific heat capacity.

THEORY DETAILS

Specific heat capacity, c, measures the heat transfer per unit of mass that is required to change the temperature of a substance:

$$c = \frac{Q}{m\Delta T}$$

This equation is more commonly expressed as follows.

$$Q = mc\Delta T$$

Q = heat transferred (J), m = mass (kg), c = specific heat capacity (J kg^{-1} K^{-1}), ΔT = change in temperature (K)

A negative value of Q indicates heat is released rather than absorbed.

Table 1 shows the approximate specific heat capacities of some common substances. Note that the specific heat capacity of a given substance is different for different states of matter (e.g. water compared to ice).

Table 1 Some common substances and their (approximate) specific heat capacities in increasing order

Substance	Specific heat capacity, c (J kg^{-1} K^{-1})
Copper	0.39×10^3
Iron	0.45×10^3
Carbon (graphite)	0.72×10^3
Air	1.0×10^3
Wood	1.8×10^3
Steam	2.0×10^3
Ice	2.1×10^3
Cooking oil	2.8×10^3
Water	4.2×10^3
Ammonia	4.7×10^3

How the mass and temperature change relate to the heat required

In Lesson 2A, we learned that temperature is a measure of the average translational kinetic energy of the particles in a substance. This means:

- The greater the increase in temperature of a given object, the greater the heat required: $Q \propto \Delta T$. See Figure 1(a).
- The greater the mass of a given substance (and hence the more particles within it), the greater the heat required to increase its temperature by a given amount: $Q \propto m$. See Figure 1(b).

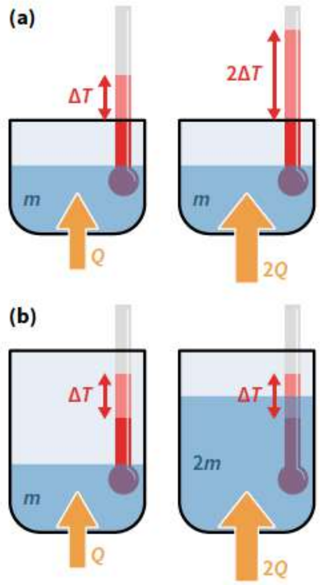


Figure 1 **(a)** Providing twice the amount of heat causes twice the temperature change in an equal mass of the same substance. **(b)** Twice the amount of heat is required to achieve the same temperature change in twice the mass of the same substance.

How the substance relates to the heat required

Different substances store their internal energy in different proportions. This means that some substances – those with higher specific heat capacities – do not change temperature as easily as others. This difference can be modelled by the difference in diameters of the blue "other energy" containers from the "energy container model" established in Lesson 2A, as shown in Figure 2 and Figure 3.

For example, water stores a greater proportion of its internal energy as "other energy" than iron does. Hence, 1 kg of water needs more heat to increase its temperature by 1 K than 1 kg of iron needs (see Figure 2) and so water has a higher specific heat capacity than iron.

[redacted]

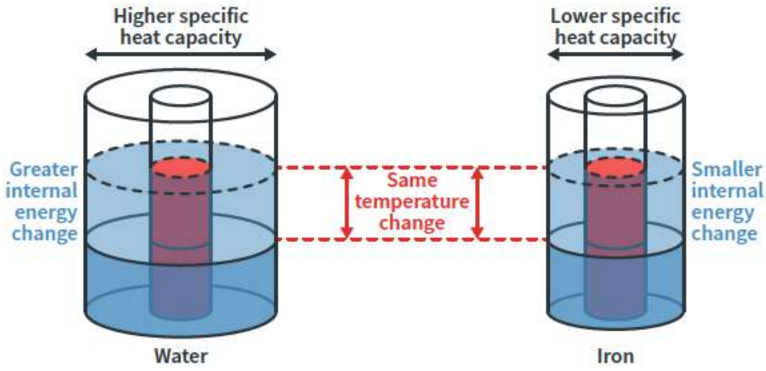


Figure 2 A substance with a higher specific heat capacity requires more internal energy to increase its temperature by the same amount as an equal mass of a substance with a lower specific heat capacity.

Similarly, if 1 kg of water and 1 kg of iron are provided with the same amount of heat, the iron's temperature will increase more than that of the water (see Figure 3).

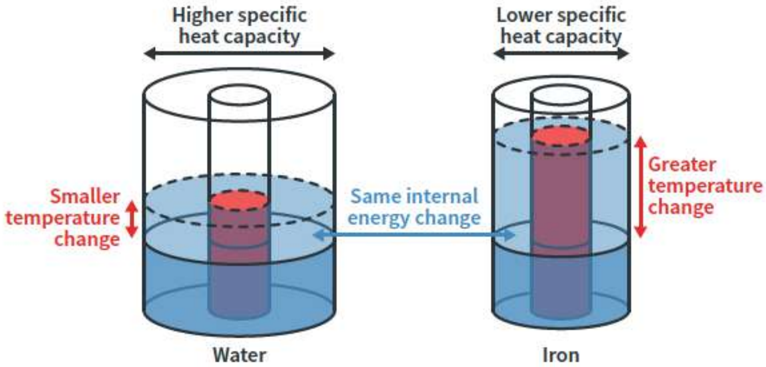


Figure 3 A substance with a higher specific heat capacity undergoes a smaller change in temperature for a given heat transfer than an equal mass of a substance with a lower specific heat capacity.

Table 2 The effect of different specific heat capacities when heating up and cooling down a fixed mass

	Heating up (absorbing heat)		Cooling down (releasing heat)	
	ΔT (for fixed Q)	Q (for fixed ΔT)	ΔT (for fixed Q)	Q (for fixed ΔT)
Higher specific heat capacity	Smaller increase	More heat absorbed	Smaller decrease	More heat released
Lower specific heat capacity	Greater increase	Less heat absorbed	Greater decrease	Less heat released

Worked example 1

For this question, take the specific heat capacity of water to be 4186 J kg^{-1} K^{-1}.

a How much energy is required to increase the temperature of 0.50 kg of water by 15°C?

b What is the final temperature (in °C) when 0.50 kg of water at an initial temperature of 30°C releases 5000 J of thermal energy?

Working	Process of thinking
a $Q = mc\Delta T$ $Q = 0.50 \times 4186 \times 15 = 31\,395$ J $Q = 3.1 \times 10^4$ J	Remember that a change of 15°C is equal to a change of 15 K. $m = 0.50$ kg, $c = 4186$ J kg^{-1} K^{-1}, $\Delta T = 15$°C $= 15$ K
b $Q = mc\Delta T$ $-5000 = 0.50 \times 4186 \times \Delta T$ $\Delta T = -2.389$ K $= -2.389$°C $T_f = T_i + \Delta T = 30 + (-2.389)$ $T_f = 28$°C	Treat heat that is released as a negative quantity. $Q = -5000$ J, $m = 0.50$ kg, $c = 4186$ J kg^{-1} K^{-1}, $T_i = 30$°C A negative value indicates a decrease in temperature.

Latent heat 1.1.7.2

OVERVIEW

Latent heat is the energy that is absorbed or released when a substance changes state. The temperature stays constant while the substance changes state.

THEORY DETAILS

In Lesson 2A, we learned that the particles in a gas have more freedom to move than the particles in a liquid, which have more freedom to move than the particles in a solid. This means that there is more potential energy stored in a gas than a liquid and in a liquid than a solid.

A solid must absorb thermal energy when it melts into a liquid and a liquid must release thermal energy when it freezes into a solid due to the difference in potential energy between these two states. Similarly, a liquid must absorb thermal energy when it boils into a gas and a gas must release thermal energy when it condenses into a liquid. These transitions are represented in Figure 4.

The temperature remains constant during transitions between states. For this reason, the energy that is absorbed or released during these transitions is called **latent heat** (which means hidden heat) – the thermal energy is 'hidden' as potential energy without any effect on the translational kinetic energy of the particles.

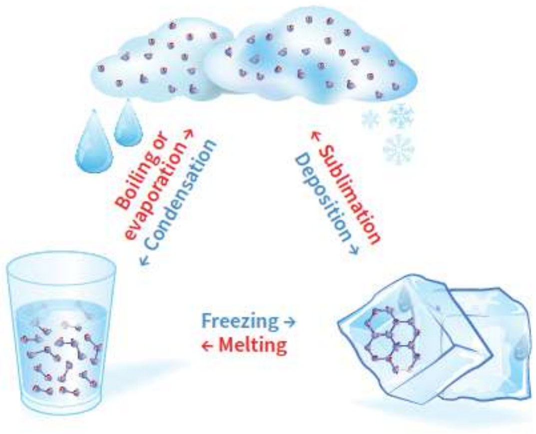


Image: Designua/Shutterstock.com

Figure 4 The transitions between states of matter. Energy must be absorbed by the substance for the processes with red arrows. Energy is released by the substance for the processes with blue arrows.

Figure 5 shows the heating curve of 1 kg of ice transitioning to water and then to steam. There are some points to note from this graph:

- The temperature does not change while the state is changing.
- The amount of thermal energy that must be absorbed to boil a liquid into a gas is exactly the same as the thermal energy that is released when the gas condenses. The same relationship is true for melting and freezing.
- For a given state, the relationship between heat and temperature is given by $Q = mc\Delta T$.

It is common to represent similar information as shown in Figure 5 with time on the horizontal axis rather than heat absorbed. This is useful when we do not know the amount of heat provided but we do know that the rate of heating is approximately constant (such as when using a Bunsen burner) so that each unit of time corresponds to a fixed amount of heat.

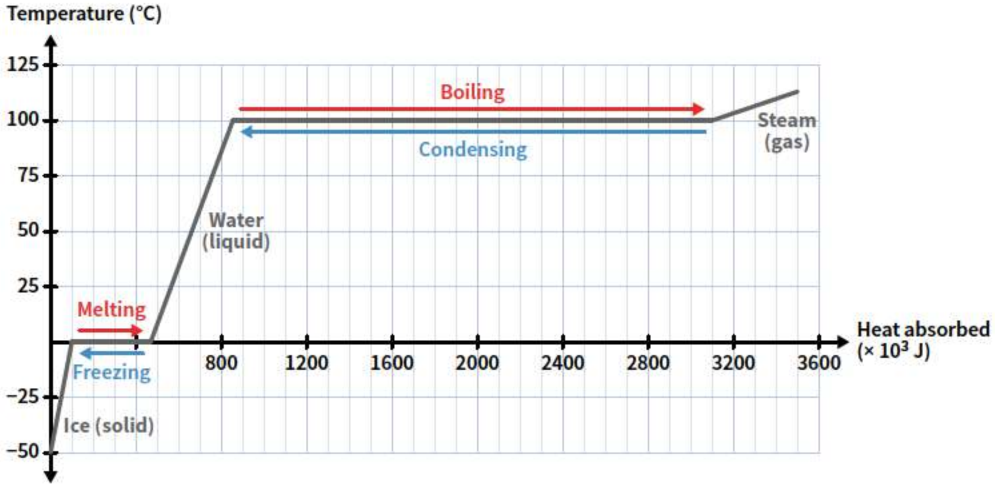


Figure 5 A heating curve for 1 kg of water

The amount of heat that is added or removed during a transition between states is given by the following equation.

$Q = mL$

Q = heat transferred (J), m = mass (kg), L = specific latent heat (J kg^{-1})

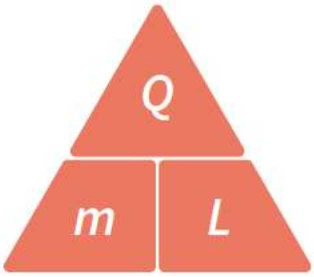


Figure 6 The formula triangle for the relationship between heat, mass, and specific latent heat

For calculations involving heat transfer, we treat heat absorbed as a positive quantity and heat released as a negative quantity. Hence, when a substance condenses from a gas to a liquid or freezes from a liquid to a solid, the latent heat is a negative quantity.

Table 3 shows the specific latent heat values for various materials. The latent heat for a transition between a solid and a liquid is called 'the latent heat of fusion'. The latent heat for a transition between a liquid and a gas is called 'the latent heat of vaporisation'.

Table 3 Some common substances and their (approximate) specific latent heat values in alphabetic order

Substance	Specific latent heat of fusion, L_f (J kg^{-1}) for solid-liquid transitions	Specific latent heat of vaporisation, L_v (J kg^{-1}) for liquid-gas transitions
(Ethyl) alcohol	1.1×10^5	8.6×10^5
Ammonia	3.3×10^5	14×10^5
Carbon dioxide	1.8×10^5	5.7×10^5
Iron	2.8×10^5	63×10^5
Oxygen	0.14×10^5	2.1×10^5
Water	3.3×10^5	23×10^5

Worked example 2

For this question, take the specific latent heat of fusion for water to be 3.34×10^5 J kg^{-1}, the specific latent heat of vaporisation for water to be 2.26×10^6 J kg^{-1}, and the specific heat capacity of water to be 4186 J kg^{-1} K^{-1}.

a Calculate how much heat must be provided to melt 2.0 kg of ice at 0°C.

b Calculate how much heat must be provided to boil 2.0 kg of water at 100°C.

c Calculate the total thermal energy required to convert 2.0 kg of ice at 0°C to steam at 100°C.

Working	Process of thinking
a $Q_{Lf} = mL_f$	Melting (converting solid to liquid) relates to the latent heat of fusion.
$Q_{Lf} = 2.0 \times 3.34 \times 10^5$ $Q_{Lf} = 6.72 \times 10^5 = 6.7 \times 10^5$ J	$m = 2.0$ kg, $L_f = 3.34 \times 10^5$ J kg^{-1}
b $Q_{Lv} = mL_v$	Boiling (converting liquid to gas) relates to the latent heat of vaporisation.
$Q_{Lv} = 2.0 \times 2.26 \times 10^6 = 4.5 \times 10^6$ J	$m = 2.0$ kg, $L_v = 2.26 \times 10^6$ J kg^{-1}
c $Q_{tot} = Q_{Lf} + Q_{water} + Q_{Lv}$	The total heat required is the sum of: the heat absorbed to melt the ice, the heat absorbed to warm the water from 0°C to 100°C, and the heat required to boil the water.
$Q_{water} = mc\Delta T$ $Q_{water} = 2.0 \times 4186 \times (100 - 0)$ $Q_{water} = 8.4 \times 10^5$ J	The heat required to warm the water is related to the temperature change by $Q = mc\Delta T$.
$\therefore Q_{tot} = 6.7 \times 10^5 + 8.4 \times 10^5 + 4.5 \times 10^6$ $Q_{tot} = 6.0 \times 10^6$ J	The latent heat for the two changes of state have been calculated in part **a** and part **b**.

Evaporative cooling 1.1.8.1

OVERVIEW

Evaporation occurs when the highest energy particles in a liquid escape from its surface. This reduces the average translational kinetic energy of the remaining particles, which means the liquid is cooler as a result of the evaporation.

THEORY DETAILS

If you are at the beach or a pool, you will notice that wind will make you feel a lot cooler if your skin is wet rather than dry. Sweating is an evolutionary mechanism that uses the same process to cool us down. This principle is called evaporative cooling. In order to understand how evaporative cooling works, we need to have a clear understanding of what evaporation is.

The difference between evaporation and boiling

Evaporation is the process of particles in a liquid escaping from the surface at a temperature below the boiling point. The particles that escape are in a gaseous state. For example, a puddle of water will evaporate and wet clothes will eventually dry without needing to reach a temperature of 100°C. This process occurs because higher-energy particles in the liquid constantly escape from its surface, as shown in Figure 7.

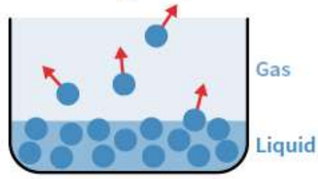


Figure 7 Evaporation occurs due to particles escaping from a liquid's surface.

The rate of evaporation is greater when:

- the temperature of the liquid is greater.
- the surrounding air is drier (lower humidity).
- air moves over the liquid surface (such as wind blowing) since it helps carry the escaped particles away.
- the surface area of the liquid is greater.
- the liquid has a lower boiling point and a lower latent heat of vaporisation since this indicates that the particles require less energy to escape.

In contrast, boiling occurs when a liquid reaches a certain temperature (and pressure) that causes the particles in the entire substance to rapidly transition from a liquid arrangement to a gaseous arrangement.

How evaporation causes cooling

Whenever a liquid evaporates it cools its surroundings. The process occurs as follows:

- The liquid absorbs heat from its surroundings (such as skin or the air), which cools the surroundings and warms the liquid.
- Higher-energy particles escape from the liquid surface to the air through evaporation.
- On average, the remaining particles in the liquid have lower translational kinetic energy than before the higher-energy particles escaped.
- This means the temperature of the liquid decreases and so more heat continues to be conducted from the surroundings to the liquid.

Evaporative cooling is used in some air conditioning systems by passing air through a damp mesh. However, this type of air conditioning is not effective in humid climates which slow the evaporative process.

Theory summary

- Temperature change is related to heat transfer by the equation: $Q = mc\Delta T$.
  - c is the specific heat capacity, which measures the heat transfer per unit of mass that is required to change the temperature of a substance by one kelvin.
- When heating up/cooling down, a substance with a higher specific heat capacity will:
  - absorb/release more heat per kelvin change in temperature (compared to an equal mass of a substance with a lower specific heat capacity).
  - change temperature by a smaller amount per joule of heat absorbed/released (compared to an equal mass of a substance with a lower specific heat capacity).
- Heat is absorbed whenever a solid turns to a liquid or a liquid turns to a gas.
  - Heat is released whenever the reverse processes occur.
  - This is called latent heat.
  - Temperature stays constant during these processes.
- Evaporative cooling occurs whenever a liquid evaporates from the surface of an object.
  - The highest energy water molecules are carried away, decreasing the average translational kinetic energy and, hence, reducing the temperature of the remaining liquid.
  - Substances with a lower specific latent heat of vaporisation and a lower boiling point tend to evaporate more quickly.

KEEN TO INVESTIGATE?

YouTube video: FuseSchool – Specific Latent Heat
youtu.be/8VmkdzRE8sQ

YouTube video: Professor Dave Explains – Heat Capacity
youtu.be/yhNHJ7WdT8A

CONCEPT DISCUSSION QUESTION

A burn caused by the steam from a kettle will generally be more severe than a burn caused by the boiling water in the kettle. Discuss why steam burns are usually worse than hot water burns even when the temperatures of the steam and the water are the same (100°C).

Answers on page 504

Hints

What causes a burn (what physical process happens) and what makes one burn more severe than another?

What is the physical difference between water at 100°C and steam at 100°C?

How does this affect the extent to which water and steam can cause burns?

2C Questions

THEORY REVIEW QUESTIONS

Question 1

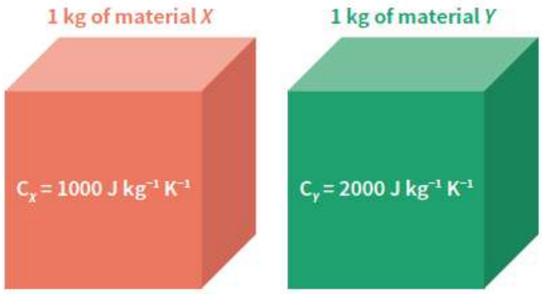
It takes 1000 J to increase the temperature of a particular brick by 10 K.

a How much heat energy is required to increase the temperature of an identical brick by 20 K?

b How much heat energy is required to increase the temperature of three identical bricks by 10 K?

Question 2

Consider a one-kilogram block of material *X* and a one-kilogram block of material *Y*, with specific heat capacities as shown in the diagram.



a If 100 J of heat is transferred to each block, which block (*X* or *Y*) will increase its temperature more?

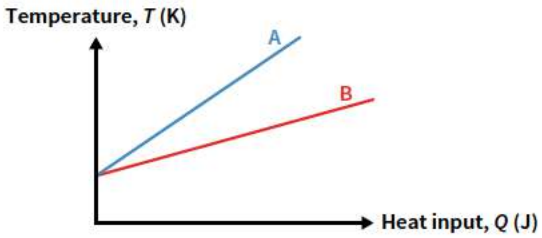
b If 100 J of heat is transferred out of each block, which block (*X* or *Y*) will decrease its temperature more?

c Which block (*X* or *Y*) must absorb the most heat to increase its temperature from 10 K to 20 K?

d Which block (*X* or *Y*) must release the most heat to decrease its temperature from 20 K to 10 K?

Question 3

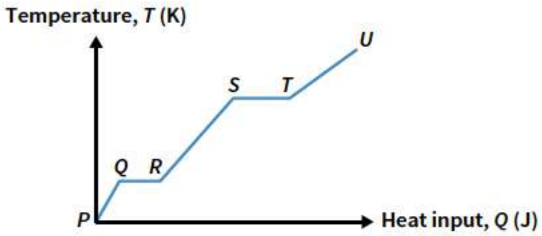
The graph shows how temperature varies for equal masses of two materials (*A* and *B*) that have the same initial temperature as they are heated.



Which material (*A* or *B*) has the higher specific heat capacity?

Question 4

The graph shows the heating curve for a particular substance.



For each of the following, fill in the gaps with the correct points on the graph.

a The process of melting from solid to liquid is represented by ________ to ________.

b The process of condensing from gas to liquid is represented by ________ to ________.

c The process of warming in the liquid state is represented by ________ to ________.

Question 5

As a substance melts from a solid to a liquid or boils from a liquid to a gas, heat is

A released by the substance.

B absorbed by the substance.

C neither absorbed nor released.

Question 6

When a substance melts, the heat is used to

A increase only the kinetic energy of the particles in the substance.

B increase only the potential energy of the particles in the substance.

C increase both the kinetic energy and potential energy of the particles in the substance.

Question 7

As a substance condenses from a gas to a liquid, or freezes from a liquid to a solid, heat is

A released by the substance.

B absorbed by the substance.

C neither absorbed nor released.

Question 8

As a substance melts from a solid to a liquid or boils from a liquid to a gas, the temperature of the substance

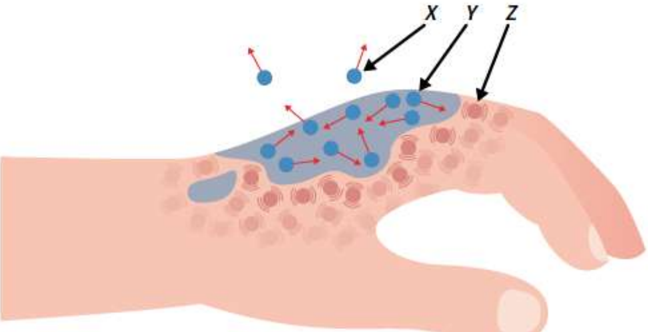
A increases.

B decreases.

C neither increases nor decreases.

Question 9

Use the diagram to fill in the following paragraph.



Putting cold water on your hand can cool your hand through evaporation. Your hand heats the water by __________ (conduction/convection/radiation), which is represented by __________ (*X*/*Y*/*Z*) in the diagram. The fastest-moving water molecules escape, which is represented by __________ (*X*/*Y*/*Z*). The slower-moving molecules remain, which is represented by __________ (*X*/*Y*/*Z*), so that the temperature of the water decreases as evaporation occurs.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 10 (4 MARKS)

100 g of water at an initial temperature of 12°C is cooled such that it releases 40 kJ of thermal energy to become ice. Take the specific heat capacity of water to be 4.2×10^3 J kg^{-1} K^{-1}, the specific heat capacity of ice to be 2.1×10^3 J kg^{-1} K^{-1}, and the latent heat of fusion for water to be 3.34×10^5 J kg^{-1} K^{-1}.

Prompts

a Which option best describes the stages of cooling that must be considered when calculating the energy that is released by the water as it turns into ice at a final temperature, T_f?

- **A** Water at 12°C cools to ice at T_f.
- **B** Water at 12°C cools to water at 0°C; ice at 0°C cools to ice at T_f.
- **C** Water at 12°C cools to water at 0°C; water at 0°C turns into ice at 0°C; ice at 0°C cools to ice at T_f.
- **D** Water at 12°C cools to water at T_f; ice at 0°C cools to ice at T_f.

b Which expression would evaluate the energy (in joules) transferred as the water cools down to 0°C?

- **A** 100×4.2
- **B** $0.100 \times 4.2 \times 10^3 \times (0 - 12)$
- **C** $0.100 \times 2.1 \times (0 - 12)$
- **D** $100 \times 4.2 \times (273.15 + 12)$

c Which expression would evaluate the change in the water's internal energy (in joules) as it turns into ice?

- **A** -100×4.2
- **B** $-0.100 \times 4.2 \times 10^3$
- **C** $0.100 \times 3.34 \times 10^5 \times (0 - 12)$
- **D** $-0.100 \times 3.34 \times 10^5$

d Which expression would evaluate the energy (in joules) transferred as the ice cools down to its final temperature, T_f?

- **A** $0.100 \times 2.1 \times 10^3 \times (T_f - 0)$
- **B** $0.100 \times 4.2 \times 10^3 \times T_f$
- **C** $0.100 \times 2.1 \times 10^3 \times (0 - 12)$
- **D** $-100 \times 2.1 \times 10^3$

Question

e Calculate the final temperature of the ice. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 11 (2 MARKS)

Calculate the heat absorbed by a graphite tennis racquet that has a mass of 0.300 kg when its temperature increases by 4.0°C. Take the specific heat capacity of graphite to be 7.2×10^2 J kg^{-1} K^{-1}.

Question 12 (2 MARKS)

The element in a toaster machine consists of 15.0 grams of nichrome wire. Electricity passing through the wire adds 5500 J of thermal energy to the wire in a short period of time. Take the specific heat capacity of nichrome to be 450 J kg^{-1} K^{-1}. Calculate the increase in temperature of the wire.

Question 13 (4 MARKS)

1.5 kg of oxygen is initially in a gaseous state at its boiling point (–183°C). Take the specific latent heat of fusion of oxygen to be 6.9×10^3 J kg^{-1} and the specific latent heat of vaporisation to be 1.1×10^5 J kg^{-1}.

a Calculate the heat released as the oxygen condenses to liquid. (2 MARKS)

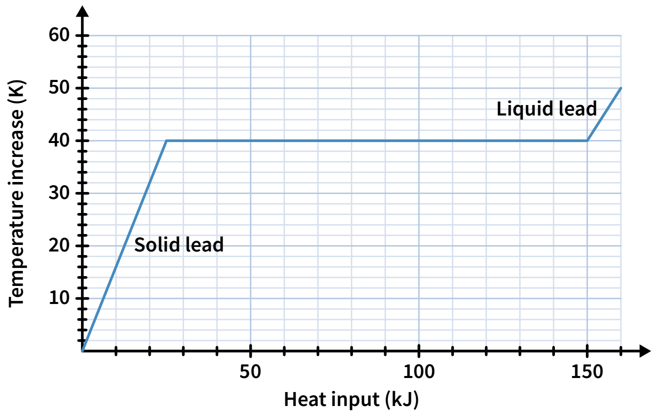
b The total amount of heat released to the surroundings as the oxygen condenses and cools is measured to be 2.0×10^5 J. How much of this thermal energy was released as a result of cooling (as opposed to condensing)? (2 MARKS)

Question 14 (3 MARKS)

Xi and Ruth are heating a beaker that initially contains a mixture of ice and water. They measure the temperature throughout the process. They notice that the mixture has a temperature of 0°C at the beginning and that the temperature is still 0°C when the last bit of ice melts. Xi says that this means the internal energy of the contents of the beaker has not changed. Ruth says that the internal energy has increased. Evaluate the two statements and justify your answer with the appropriate physics principles.

Question 15 (7 MARKS)

The graph shows the heating curve for 5.0 kg of lead as it melts to a liquid.



a Calculate the gradient of the section of the graph corresponding to solid lead. Provide your answer in K J^{-1} to two significant figures. (2 MARKS)

b Using the data in the graph, calculate the specific heat capacity of solid lead. Provide your answer to two significant figures. (3 MARKS)

c Use the graph to calculate the specific latent heat of fusion for lead. Provide your answer to two significant figures. (2 MARKS)

Use the following data table to answer Questions 16–19.

Substance	Water	Glass	Rubbing alcohol
Specific latent heat of fusion, L_f (J kg^{-1})	3.3×10^5	–	–
Specific latent heat of vaporisation, L_v (J kg^{-1})	2.3×10^6	–	8.5×10^5
Specific heat capacity, c (J kg^{-1} K^{-1})	4.2×10^3	840	–
Melting point (°C)	0	–	–
Boiling point (°C)	100	–	79

Question 16 (3 MARKS)

0.90 kg of ice at 0°C is provided with 4.0×10^5 J of heat so that it completely melts. Calculate the final temperature (in °C) of the water.

Question 17 (3 MARKS)

Calculate the increase in temperature of a 4.0 kilogram glass window when 50 grams of steam at 100°C condenses to water at 100°C on its surface. Assume there are no heat transfers other than from the steam to the glass.

Question 18 (5 MARKS)

200 g of ice at 0°C is added to 1.2 kg of water at 20°C in a thermally insulated container. Eventually the ice melts and thermal equilibrium is reached so there is only water in the container at a final temperature between 0°C and 20°C. What is the final temperature of the contents of the container?

Question 19 (3 MARKS)

Explain the relevant physics principles behind the observation that rubbing alcohol cools your skin more quickly than water.

Previous lessons

Question 20 (1 MARK)

The temperature in the clouds of Jupiter is –145°C. Provide this temperature in SI units.

Question 21 (2 MARKS)

The difference in temperature between object A and object B is initially 400 K. After a period of time, the difference in temperature is only 100 K. By what factor has the rate of heat transfer $\frac{Q}{\Delta t}$ changed?

Key science skills

Question 22 (8 MARKS)

Students conduct an experiment to measure the effect that known quantities of heat have on water. They heat 0.400 kg of water in a beaker and measure the temperature for every 10 kJ of heat that is added. They record the following data. Assume that the temperature measurements have an uncertainty of ±2°C, but the heat measurements are known to a high degree of accuracy.

Heat input (kJ)	0	10	20	30	40	50
Temperature (°C)	20	25	31	36	40	45

a Plot the data on a graph with heat input on the horizontal axis and temperature on the vertical axis. Include axis labels (with units), an appropriate scale, uncertainty bars, and a line of best fit. (5 MARKS)

b Use the gradient of the line of best fit to estimate the specific heat capacity of water. (3 MARKS)

2D THE ZEROTH AND FIRST LAWS OF THERMODYNAMICS

The laws of thermodynamics collectively describe the way that energy flows and interacts with matter. This lesson will build upon the understanding of internal energy and heat flow that we have developed in this chapter so far to study the first two of these laws.

2A What is temperature?	2B How does thermal energy move?	2C How heat affects temperature	2D The Zeroth and First Laws of Thermodynamics

Study design dot points

- describe the Zeroth Law of Thermodynamics as two bodies in contact with each other coming to a thermal equilibrium
- investigate and apply theoretically and practically the First Law of Thermodynamics to simple situations: $Q = U + W$

Key knowledge units

The Zeroth Law of Thermodynamics	1.1.2.1
Work done	1.1.4.1
The First Law of Thermodynamics	1.1.4.2

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$W = Fs$ work done
	$\Delta U = Q + W$ change in internal energy
	$\Delta U = mc\Delta T$ internal energy change due to temperature change

The Zeroth Law of Thermodynamics 1.1.2.1

OVERVIEW

If two systems are each in thermal equilibrium with a third system, they are also in equilibrium with each other.

THEORY DETAILS

Recall from Lessons 2A and 2B that thermal equilibrium describes a state where there is no net heat transfer between two systems that are in thermal contact, which occurs when the two systems are at the same temperature.

The Zeroth Law of Thermodynamics states that if two systems, A and B, are each in thermal equilibrium with a third system, C, then A and B are also in thermal equilibrium with each other.

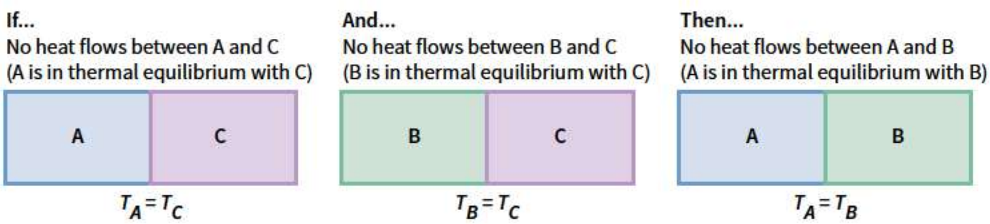


Figure 1 A visual representation of the Zeroth Law of Thermodynamics

The Zeroth Law is needed to define the concept of a temperature scale as a means of indicating the direction of heat flow between systems. If, for example, heat flows from system A to system C and from system C to system B then we can conclude that system A has a higher temperature than system B.

Work done 1.1.4.1

OVERVIEW

Work is a change in energy caused by a component of force pushing in or against the direction of motion. When work is done due to a force that pushes on the boundary of a system, it changes the internal energy of the system.

THEORY DETAILS

When a force is applied to an object in or against the direction of motion, there are two possible effects depending on the situation:

- **Effect 1:** The object will speed up or slow down, which means its kinetic energy changes.
- **Effect 2:** The object's position changes in a region within which a force (such as an electrostatic, gravitational, or spring force) exists, which means its potential energy changes.

In each case, these changes have an associated change in energy. We refer to this change in energy as 'work'.

Work can be calculated as:

$$W = Fs$$

W = work done (J), F = magnitude of force parallel to motion (N), s = distance moved (m)

- When work is done such that the energy of an object increases, we say that 'work is done on the object'.
- When work is done such that the energy of the object decreases, we say that 'work is done by the object.'

The concept of work will be explored for larger-scale objects in more detail in Lesson 10B.

We now consider the concept of work being done on systems of small particles due to a force that changes the boundary (or shape) of the system. As an example, the system could be a cylinder with a plunger (like a piston) filled with air particles as shown in Figure 2.

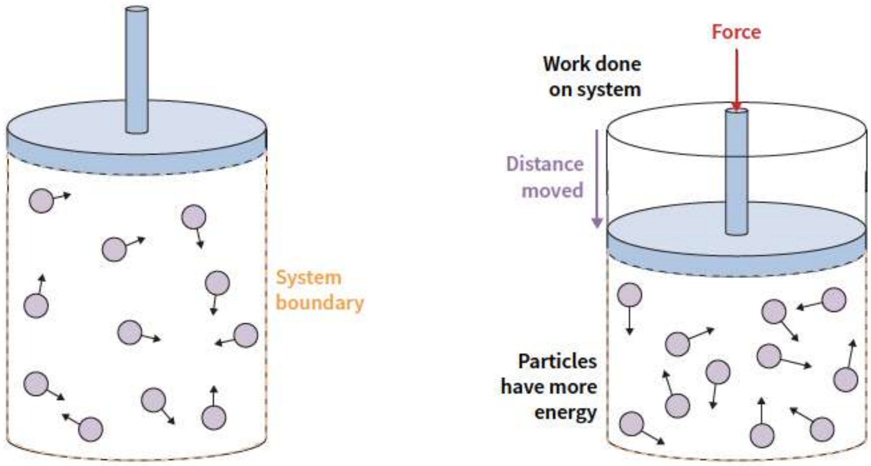


Figure 2 Work is done on a system when a force is applied to its boundary that causes the volume to decrease. The average energy of the particles increases.

Work is done on a system of small particles when a force is applied to the boundary of the system so that the volume of the system decreases.

- As the boundary closes in on the particles, it causes more frequent collisions with the particles so the particles move faster (the kinetic energy increases) and the potential energy increases.
- That is, the internal energy increases (which is associated with a temperature increase).

The reverse process is also true: work is done by the system when the volume of the system increases, which means that the internal energy decreases.

The First Law of Thermodynamics 1.1.4.2

OVERVIEW

The change in internal energy of a system is equal to the amount of energy that has been transferred to or from it due to heat transfer or work being done.

THEORY DETAILS

The First Law of Thermodynamics is a statement that energy is conserved as it crosses a system's boundary. In Lesson 2B we learned that the internal energy of a system increases when heat is transferred to it and decreases when heat is transferred away from it. In the previous section we also learned how the internal energy changes due to work being done on or by the system. The First Law of Thermodynamics can be expressed by the following equation:

$$\Delta U = Q + W$$

ΔU = change in internal energy (J), Q = net heat transferred to system (J), W = net work done on system (J)

It is worth emphasising the difference between heat and work done:

- Heat is the **transfer of thermal energy** from one system to another.
- Work is the transformation or transfer of energy **due to a force**. In the context of the First Law of Thermodynamics, work is the **transformation of mechanical energy** to **thermal energy** or the reverse transformation.

Note that Q in the equation represents the net heat transfer into the system, which means that it is the difference between the heat transferred into the system and the heat that is transferred out of the system. That is, $Q = Q_{in} - Q_{out}$.

Similarly, W represents the net work done. For simplicity, in this book we treat the work done as a positive quantity when it increases the internal energy of the system (when the work done **on** the system is greater in magnitude than the work done **by** the system). That is: $W = W_{on} - W_{by}$.

However it is also common to see the First Law of Thermodynamics written as $\Delta U = Q - W$ (or $Q = U + W$, as in the VCE Study Design), in which case work done by the system is considered a positive quantity. The conventions used in this book are represented in Figure 3.

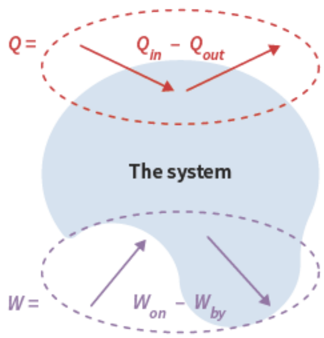


Figure 3 We define heat into the system and work done by the system as positive quantities for the purposes of the First Law of Thermodynamics since they both lead to increases in the internal energy. Heat is considered to be negative when it flows out of the system and work is considered to be negative when it is done by the system.

Worked example 1

A balloon filled with air has 2.0 J of work done on it. During this process it transfers 0.5 J of heat to its surroundings. What is the change in internal energy of this balloon system?

Working

$\Delta U = Q + W$

$\Delta U = (-0.5) + 2.0 = 1.5$ J

Process of thinking

$Q = -0.5$ J. It is a negative value since the heat is transferred out of the balloon to the surroundings.

$W = 2.0$ J. It is a positive value since the work is done on the system.

In Lesson 2C we learned that the relationship between heat transfer and the change in temperature of a substance is given by $Q = mc\Delta T$ (when there is no change in state). This equation assumes that there is no work done on the substance. A more accurate relationship is $\Delta U = Q + W = mc\Delta T$, which shows how work can change the temperature of a system too.

$$\Delta U = mc\Delta T$$

ΔU = change in internal energy (J), m = mass (kg), c = specific heat capacity (J kg^{-1} K^{-1}), ΔT = change in temperature (K)

Theory summary

- The Zeroth Law of Thermodynamics states that if two systems are each in thermal equilibrium with a third system, they are also in equilibrium with each other.
- Work is a transfer of energy that is caused by a component of a force acting parallel to the direction of motion.
  - When work is done such that the internal energy of a system **increases**, we say that work is done **on** the system.
  - When work is done such that the internal energy of a system **decreases**, we say that work is done **by** the system.
- The First Law of Thermodynamics states that energy is conserved.
  - The internal energy of a system changes due to heat transfer and work being done.
  - If we define heat transfer to the system as positive and work done on the system as positive, then $\Delta U = Q + W$.

KEEN TO INVESTIGATE?

PhET 'Gas Properties' simulation
phet.colorado.edu/en/simulation/gas-properties

YouTube video: CrashCourse – The First and Zeroth Laws of Thermodynamics
youtu.be/fSEFfWf2au0

CONCEPT DISCUSSION QUESTION

Discuss the reason that a bicycle pump will tend to feel warm when you use it, especially if you pump the tyre quickly.

Answers on page 504

Image: kontur-vid/Shutterstock.com

Hints

If we consider the air in a bicycle pump as the system, what are you doing to that system when you push the piston down?

What effect does this have on the internal energy and the temperature of the system?

What physical process must happen for the pump to 'feel warm'?

2D Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–3.

A block of metal is in thermal equilibrium with a block of wood. The block of wood is also in thermal equilibrium with a brick.

Question 1

What can be said about the block of metal and the block of wood?

A There is no net heat transfer between them when they are in thermal contact.

B The forces on each block are balanced.

Question 2

What can be said about the block of wood and the brick?

A They have the same mass.

B They have the same temperature.

Question 3

Which of the following statements is true about the block of metal and the brick?

A They are also in thermal equilibrium.

B We need to know their temperatures to determine the direction heat would flow between them.

Question 4

Identify the two methods of energy transfer that can change the internal energy of a system.

Question 5

When a balloon containing air is compressed (without losing air from the balloon)

A work is done by the air in the balloon.

B work is done on the system air in the balloon.

Question 6

What effect does compressing a balloon containing air (without losing air from the balloon) have on the internal energy of the system?

A The internal energy increases.

B The internal energy decreases.

C There is no effect.

Question 7

What happens to the internal energy of the air inside a balloon when the balloon expands (without gaining air)?

A The internal energy increases.

B The internal energy decreases.

C There is no effect.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (3 MARKS)

2.0 kg of compressed gas in a cylinder does 0.800 kJ of work on its surroundings as the cylinder expands. During this expansion, the gas also gains 300 J of heat from its surroundings. Assume that the gas has a constant specific heat capacity of 1.0×10^3 J kg^{-1} K^{-1} throughout the process.

Prompts

a Which equation correctly shows the change in internal energy (measured in joules) of the gas?

A $\Delta U = 300 + 800$

B $\Delta U = 300 - 800$

C $\Delta U = -300 + 800$

D $\Delta U = -300 - 800$

b How does the change in internal energy relate to the change in temperature?

A $\Delta U = \Delta T$

B $\Delta U = -\Delta T$

C $\Delta U = \frac{1}{2}m\Delta T^2$

D $\Delta U = mc\Delta T$

Question

c Calculate the change in temperature of the gas. Provide your answer in kelvin. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (2 MARKS)

A container of water is in thermal equilibrium with a gas canister. When the container of water is placed in thermal contact with a cube of steel, heat flows from the water to the steel.

a In which direction would heat flow (from which system to which system), if at all, when the gas canister and the cube of steel are placed in thermal contact? (1 MARK)

b What can be said about the relative temperature of the gas canister and the cube of steel before they are in thermal contact? (1 MARK)

Question 10 (3 MARKS)

Determine the change in internal energy of the gas in the following situations.

a A gas in a fixed container is heated by 300 J. (1 MARK)

b 150 J is used to move the piston of a well-insulated cylinder (so heat cannot transfer) to expand the volume of the cylinder. (1 MARK)

c A plunger does 420 J of work to compress a gas, while the gas transfers 180 J of heat to its surroundings. (1 MARK)

Question 11 (1 MARK)

A student named X Æ A-12 does 2400 J of work climbing some stairs. The exercise causes her temperature to increase so she also releases 3300 J of heat in the process. What is the change in X Æ A-12's internal energy?

Question 12 (3 MARKS)

The internal energy of gas in a balloon decreases by 500 J when the balloon is cooled so that 800 J of heat is transferred from the balloon to its surroundings. Determine whether work is done **on** the balloon or **by** the balloon in this situation. Calculate how much work is done.

Question 13 (3 MARKS)

A syringe filled with gas does 72 J of work on its surroundings as it expands. The internal energy of the gas in the syringe decreases by 40 J. Determine whether heat has been transferred **to** the gas in the syringe or **away** from it and how much heat has been transferred.

Question 14 (3 MARKS)

In her excitement while learning about the Zeroth Law of Thermodynamics, Fatima does 1200 J of work on her bottle containing 0.75 kg of cold water. The water also gains 100 J of heat from the surroundings. Calculate the increase in temperature of the water during this process. Provide your answer in degrees Celsius. Take the specific heat capacity of water to be 4.2×10^3 J kg^{-1} K^{-1}.

Previous lessons

Question 15 (2 MARKS)

With reference to the appropriate form of heat transfer, explain why air conditioning systems are commonly placed at a high position in buildings (high on the wall or in the ceiling, for example).

Question 16 (2 MARKS)

Calculate the energy absorbed by 0.120 kg of water at 65°C as it warms up to 100°C and boils to steam at 100°C. Take the specific heat capacity of water to be 4.2×10^3 J kg^{-1} K^{-1} and the specific latent heat of vaporisation of water to be 2.3×10^6 J kg^{-1} K^{-1}.

Key science skills

Question 17 (3 MARKS)

Lucy conducts an experiment in which she measures the effect that doing work on a gas has on the internal energy of the gas. She does work on a volume of the gas by compressing a syringe. She measures the change in temperature of the gas and uses this measurement to calculate the change in internal energy (with a known value of specific heat capacity for the gas). She expects to find that the change in internal energy will be equal to the work done. Her results are shown in the table.

W (J)	10	20	30	40
ΔU (J)	8	17	25	32

What type of error is responsible for the difference between the work done and the change in internal energy? Explain your answer and suggest a cause of this error.

CHAPTER 2 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Which option is closest to a temperature of 1000 K?

A 727°C

B 1000°C

C 1273°C

D 1843°C

Question 2

Lloyd notices that, on a cold day, the tiles in his bathroom feel very cold on his feet. He puts on a pair of thick socks to stop his feet getting so cold. Which form of **heat transfer** do the socks affect the most in this situation?

A Conduction

B Convection

C Contact

D Radiation

Question 3

An iPhone is in thermal equilibrium with a Samsung Galaxy. The Samsung Galaxy is at the same temperature as a Huawei. Choose the statement that best describes this situation.

A The iPhone is at the same temperature as the Samsung Galaxy.

B There is no net heat transfer between the Samsung Galaxy and the Huawei.

C The iPhone is in thermal equilibrium with the Huawei.

D All of the above

Question 4

Which of the following statements is the best explanation for the reason that a beaker of water stays at a constant temperature while it is boiling due to a Bunsen flame?

A The internal energy of the water stays constant during the process of boiling.

B The heat is used to increase the potential energy of the particles in the water so the average kinetic energy of the particles stays constant.

C The water loses energy at the same rate as it absorbs energy from the flame.

D The increase in kinetic energy of the particles is offset by a decrease in the potential energy of the particles.

Question 5

The air in a car tyre absorbs 4.0 J of energy due to radiation from the Sun. The air does 1.2 J of work as its volume slightly increases. What is the change in internal energy of the air in the tyre?

A It decreases by 5.2 J.

B It decreases by 2.8 J.

C It increases by 2.8 J.

D It increases by 5.2 J.

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

With reference to the kinetic theory of matter, explain why a pocket of warm air that is surrounded by cooler air will rise.

Question 7 (5 MARKS)

A large goblet made of aluminium with a mass of 120 grams is at temperature of 25.0°C. Chilled water at 5.0°C is poured into the goblet. In a short time, the goblet has cooled down to 10.0°C. Assume that the goblet and the water are an isolated system (so that there is no heat exchanged with the surrounding environment) and that heat is distributed evenly within each substance. Take the specific heat capacity of aluminium to be $c_{al} = 900\ \text{J kg}^{-1}\ \text{K}^{-1}$ and the specific heat capacity of water to be $c_w = 4.18 \times 10^3\ \text{J kg}^{-1}\ \text{K}^{-1}$.

a Calculate the amount of heat transferred from the goblet. (2 MARKS)

b If the water has a temperature of 6.9°C when the goblet has reached 10.0°C, calculate the mass of the water that was poured into the goblet. Provide your answer in grams. (3 MARKS)

Question 8 (3 MARKS)

Tobias notices that, when his skin is wet, his skin feels much cooler when the wind blows than when the air is still. Use a simple kinetic energy model to explain this observation.

Question 9 (4 MARKS)

A solid iron block with a mass of 10.0 kg is at a temperature of 1538°C, which is its melting point, but none of the block has melted. 3.00×10^6 J of heat is provided to the block. Use the data table provided to answer the following questions.

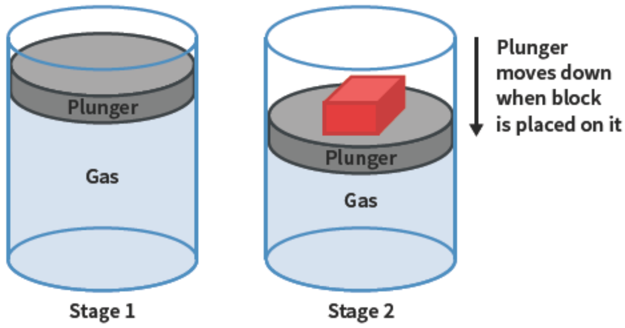
Specific heat capacity of solid iron	$4.45 \times 10^2\ \text{J kg}^{-1}\ \text{K}^{-1}$
Specific heat capacity of liquid iron	$8.20 \times 10^2\ \text{J kg}^{-1}\ \text{K}^{-1}$
Specific latent heat of fusion for iron	$2.47 \times 10^5\ \text{J kg}^{-1}$

a Show that the amount of heat required to melt the iron block is 2.47×10^6 J. (1 MARK)

b Calculate the final temperature of the liquid iron. (3 MARKS)

Question 10 (7 MARKS)

A container that is initially uninsulated is fitted with a plunger. The container is filled with gas and the plunger is positioned at the top (stage 1). A block is then placed on the plunger so that it moves to a lower position (stage 2). During the process between stage 1 and stage 2, 40 J of work is done on the gas inside and the internal energy of the gas increases by 10 J. Assume that gas cannot escape from the container and friction is negligible.



a Calculate the amount of heat transferred as the plunger moves downwards and determine whether the heat is transferred **to** the gas or **from** the gas. (3 MARKS)

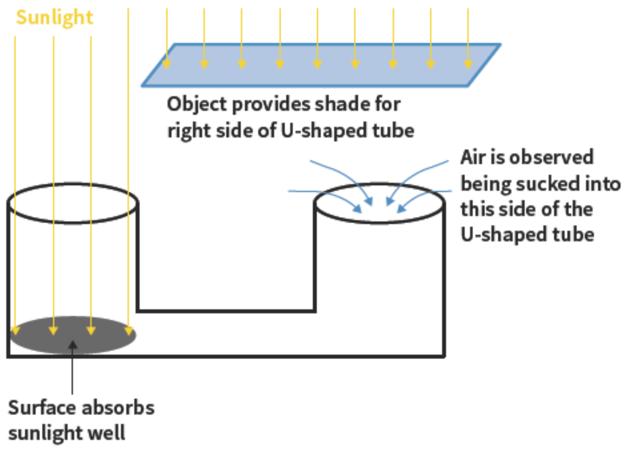
b Compare the temperature of the gas at stage 2 with its initial temperature at stage 1. Justify your answer. (2 MARKS)

c As soon as the process is completed, the container is insulated so that no more heat can transfer to or from the gas. Then the mass is removed and the plunger moves upwards (stage 3). Compare the internal energy of the gas at stage 3 with its internal energy at stage 2. Justify your answer. (2 MARKS)

Question 11 (4 MARKS)

Students are conducting an experiment in which a U-shaped tube is placed in the sunlight. The bottom of the left side of the tube has a matte black surface, which absorbs sunlight very effectively. The students place an object above the right side of the tube so that the right side is not in direct sunlight. They use a smoke stick to observe that air appears to be drawn into the top of the right side of the tube, as shown in the diagram.

Explain the roles of the appropriate forms of heat transfer that lead to air being drawn into the right side of the tube.



UNIT 1 AOS 1, CHAPTER 3

Earth's climate

03

3A **The electromagnetic spectrum**

3B **Thermal radiation**

3C **Earth's energy flow**

3D **The greenhouse effect**

3E **Modelling effects on the climate**

3F **Thermodynamic principles in housing and transportation**

Key knowledge

- identify regions of the electromagnetic spectrum as radio, microwave, infrared, visible, ultraviolet, x-ray and gamma waves
- describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared
- calculate the peak wavelength of the re-radiated electromagnetic radiation from Earth using Wien's Law: $\lambda_{max} T = \text{constant}$
- compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures such as the Sun
- describe power radiated by a body as being dependent on the temperature of the body according to the Stefan-Boltzmann Law, $P \propto T^4$
- explain the roles of conduction, convection and radiation in moving heat around in Earth's mantle (tectonic movement) and atmosphere (weather)
- model the greenhouse effect as the flow and retention of thermal energy from the Sun, Earth's surface and Earth's atmosphere
- explain how greenhouse gases in the atmosphere (including methane, water and carbon dioxide) absorb and re-emit infrared radiation
- analyse changes in the thermal energy of the surface of Earth and of Earth's atmosphere
- analyse the evidence for the influence of human activity in creating an enhanced greenhouse effect, including affecting surface materials and the balance of gases in the atmosphere
- apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity with reference to the enhanced greenhouse effect:
  - proportion of national energy use due to heating and cooling of homes
  - comparison of the operation and efficiencies of domestic heating and cooling systems: heat pumps; resistive heaters; reverse-cycle air conditioners; evaporative coolers; solar hot water systems; and/or electrical resistive hot water systems
  - possibility of homes being built that do not require any active heating or cooling at all
  - use of thermal imaging and infrared thermography in locating heating losses in buildings and/or system malfunctions; cost savings implications
  - determination of the energy ratings of home appliances and fittings: insulation; double glazing; window size; light bulbs; and/or electrical gadgets, appliances or machines
  - cooking alternatives: appliance options (microwave, convection, induction); fuel options (gas, electricity, solar, fossil fuel)
  - automobile efficiencies: fuel options (diesel petrol, LPG and electric); air delivery options (naturally aspirated, supercharged and turbocharged); and fuel delivery options (common rail, direct injection and fuel injection)
- explain how concepts of reliability, validity and uncertainty relate to the collection, interpretation and communication of data related to thermodynamics and climate science.

Image: Yvonne Baur/Shutterstock.com

3A THE ELECTROMAGNETIC SPECTRUM

This lesson will introduce the electromagnetic spectrum and identify its different regions. Many modern technologies, from mobile phones to medical equipment, as well as our ability to see light, use the electromagnetic spectrum.

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot point

- identify regions of the electromagnetic spectrum as radio, microwave, infrared, visible, ultraviolet, x-ray and gamma waves

Key knowledge unit

The electromagnetic spectrum	1.1.9.1

No previous or new formulas for this lesson

Definitions for this lesson

electromagnetic spectrum the range of all electromagnetic waves ordered by frequency and wavelength

electromagnetic wave a disturbance in the electric and magnetic fields (electromagnetic fields) of charged particles; includes visible light

frequency the number of cycles completed per unit time

wavelength the distance between two identical points in a wave

The electromagnetic spectrum 1.1.9.1

OVERVIEW

The electromagnetic spectrum describes all the types of electromagnetic waves in order of frequency.

THEORY DETAILS

What is an electromagnetic wave?

Electromagnetic waves (also called electromagnetic radiation) are energy-carrying disturbances in electric and magnetic fields. They have the following properties:

- They do not need a medium to propagate.
  - This means they can travel through the vacuum of space.
- They all travel at the same speed in a vacuum – the speed of light.
- They can be created by the acceleration of charged particles.
  - This will be further explored in Lesson 7B.
- They exhibit common behaviours of reflection, absorption, and transmission.
- They all have a frequency, with an associated wavelength and energy.

Electromagnetic waves have many applications from radios and Wi-Fi to the study of molecular structure.

Wavelength

Wavelength, λ, defines the length of the wave from one crest (highest point) or trough (lowest point) to the next; see Figure 1. The SI unit for wavelength is metres (m).

For electromagnetic waves, the longest wavelengths can be hundreds of kilometres long and the smallest could be smaller than an atom.

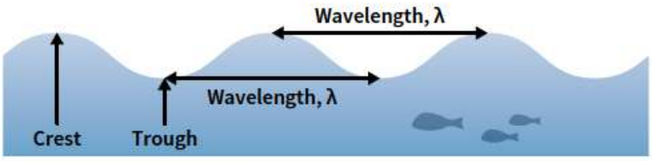


Figure 1 The wavelength of a wave shown as the distance between two of its highest points or two of its lowest points

Frequency

Frequency, *f*, defines the number of wavelengths that pass a point every second. The SI unit for frequency is hertz (Hz). One hertz is defined as one complete cycle per second ($1\ Hz = 1\ s^{-1}$). Higher frequencies correspond to shorter wavelengths and lower frequencies correspond to longer wavelengths. We use frequency to categorise the different ranges of the electromagnetic spectrum. For example, visible light falls between 4.0×10^{14} Hz and 8.0×10^{14} Hz.

Energy of electromagnetic waves

One of the most important qualities of electromagnetic waves is that they carry energy; and different parts of the spectrum carry different amounts of energy. The **higher** the frequency (the **shorter** the wavelength) of the wave, the **higher** the energy.

We can model this principle with a boat floating on top of ocean waves, as seen in Figure 2. Assume the waves all have the same height. If there is a long time between wave peaks (low frequency, long wavelength), the boat gently sways – the waves have low energy. However, if the time between waves is short (high frequency, short wavelength) the boat rocks more vigorously – the waves have high energy.

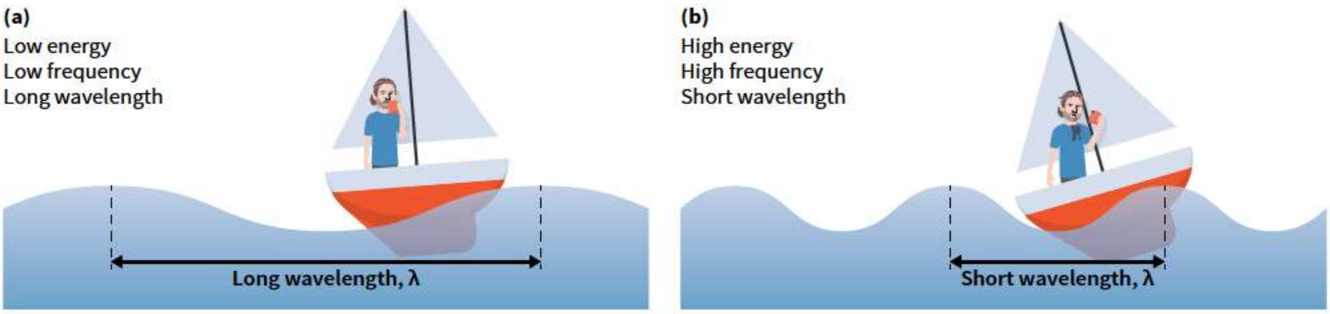


Figure 2 **(a)** Lower frequency, longer wavelength waves have a lower energy compared to **(b)** higher frequency, shorter wavelength waves, which have a higher energy.

The electromagnetic spectrum

The electromagnetic spectrum is the range of all electromagnetic waves. The spectrum can be categorised by frequency into different regions – radio wave, microwave, infrared, visible, ultraviolet, X-ray, and gamma waves – as shown in Figure 3.

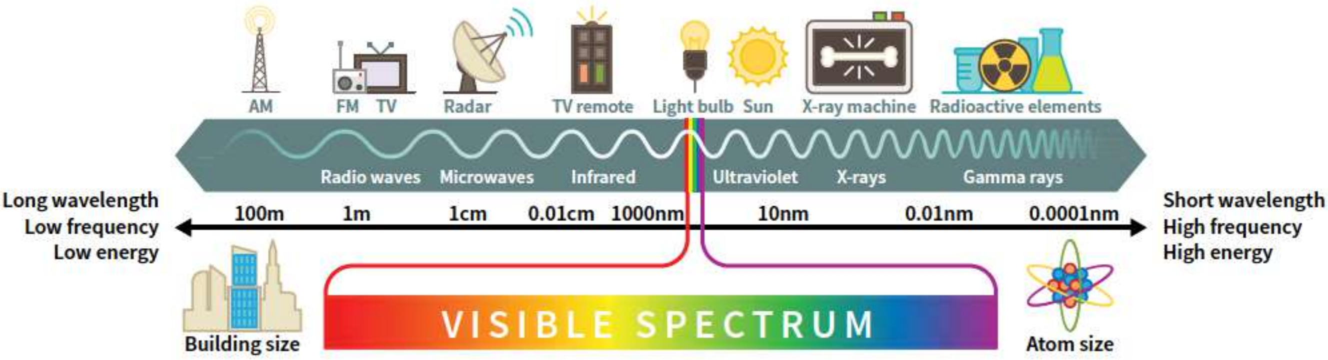


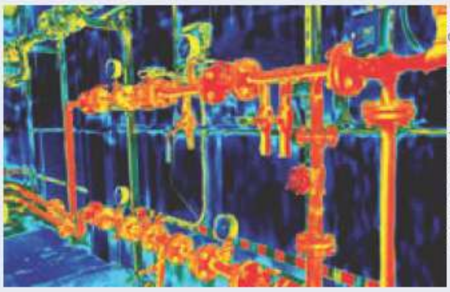
Image: VectorMine/Shutterstock.com

Figure 3 The electromagnetic spectrum

The different frequencies (or wavelengths) of the regions of the electromagnetic spectrum determine whether (and how much) the waves are transmitted, reflected, or absorbed when they interact with a given substance. This affects other properties of the waves such as how far they travel through substances, how much damage they do to our cells, and whether we can see them.

It is common to refer to all types of electromagnetic radiation as 'light'. We call light that we can see '**visible**' light. This is a very small region of the entire spectrum. Table 1 provides some uses and properties of the regions of the electromagnetic spectrum.

Table 1 The electromagnetic spectrum in order of increasing energy

Name	Details and examples
Radio waves	• Radio and television signals • Note that the radio wave is not the sound from a radio itself; it is the signal that carries information between the radio antennas. • Due to their low energy/long wavelength, they do not get absorbed easily so they transmit long distances through a material medium.
Microwaves	• Cooking food, Wi-Fi, and mobile phone signals
Infrared	• TV remote controls, thermal cameras  Image: Valery Lisin/Shutterstock.com
Visible	• The range of the spectrum that we can see
Ultraviolet	• "Black" lights (used in forensic investigations) • Can damage biological cells (sunburn and, with prolonged exposure, cancer)
X-radiation (X-rays)	• Imaging of bone structures • Light at this wavelength passes easily through soft tissues  Image: itsmejust/Shutterstock.com
Gamma radiation	• Used in medical procedures to target and kill tumour cells • Produced by nuclear reactions and cosmic objects • Due to their very high energy/short wavelength, they are easily absorbed so they do not transmit far through a material medium.

Theory summary

- Electromagnetic waves carry energy at the speed of light. They are created when charged particles accelerate and can travel through a vacuum (without a medium).
- The electromagnetic spectrum can be divided into seven regions according to frequency (or wavelength). They are, from lowest to highest frequency/energy (longest to shortest wavelength):
  - Radio waves, microwaves, infrared radiation, visible light, ultraviolet light, X-rays, gamma rays

KEEN TO INVESTIGATE?

YouTube video: BestOfScience – The Electromagnetic Spectrum
youtu.be/cfXzwh3KadE

YouTube video: Bozeman Science – Electromagnetic waves
youtu.be/WNkB8IY-k04

YouTube video: NASA Goddard – X-Class: A Guide to Solar Flares
youtu.be/oOXVZo7KikE

CONCEPT DISCUSSION QUESTION

Radio waves and microwaves are used to communicate information, such as the information of your voice between mobile phones. Other regions of the electromagnetic spectrum could carry information in the same way. Discuss why visible light and gamma waves, for example, are not used in communication technology in the same way as radio waves and microwaves.

Answers on page 504

Hints

What property must an information-carrying signal have in order to reach its destination?

What other properties are important for an information-carrying signal, given that there are always many such signals travelling around us at a time?

What are the properties of visible light or gamma waves, for example?

3A Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following options lists the electromagnetic spectrum from the fastest wave to slowest wave in a vacuum?

A Gamma rays, X-rays, ultraviolet, visible, infrared, microwaves, radio waves

B Radio waves, microwaves, infrared, visible, ultraviolet, X-rays, gamma rays

C They all travel at random speeds and therefore it is impossible to rank them.

D They all travel at the same speed.

Question 2

Fill in the gaps in the following paragraph.

Phones release low energy electromagnetic waves: the screens emit __________ (visible light/gamma waves) and the antennas emit __________ (X-rays/microwaves) to transmit information. Unlike high energy waves such as __________ (visible light/gamma waves) and __________ (X-rays/microwaves), the low energy waves are safe in large quantities.

Question 3

Which of the following statements about radio waves, microwaves, infrared, visible, ultraviolet, X-ray, and gamma rays is **false**?

A They are all examples of electromagnetic waves.

B They are all different with no shared properties.

C They all exist on a spectrum and have some common properties.

Question 4

We can model how a radio transforms radio waves into sound as the translation of verbal language into sign language.

Image: Anthony Correia/Shutterstock

As the presenter speaks, the interpreter translates the information into Auslan (sign language) so that deaf people can access the information.

Match the stages of translating verbal language into sign language with the stages of transforming a radio signal into sound (shown in an incorrect order).

Transforming a radio signal into sound

- Radio emits sound
- Radio station sends a radio wave signal
- Radio receives radio waves

Translating verbal language into sign language

a Presenter speaks

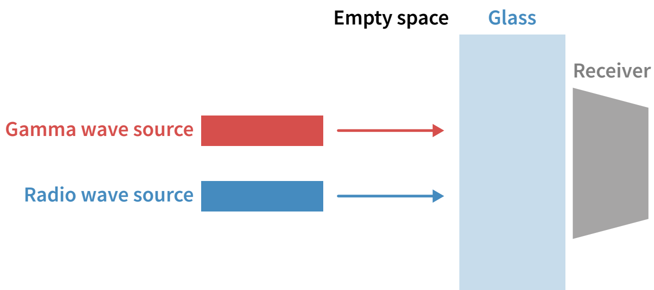
b Translator hears the spoken words

c Translator communicates in sign language

DECONSTRUCTED EXAM-STYLE QUESTION

Question 5 (4 MARKS)

A burst of radio waves and gamma waves are sent from an electromagnetic source to a receiver. For the first half of the distance from the source to the receiver, the waves travel through empty space (a vacuum). For the second half, the waves travel through glass.



Prompts

a What is the difference between gamma waves and radio waves?

A Gamma waves are electromagnetic waves whereas radio waves are sound waves.

B Gamma waves can be seen whereas radio waves are invisible.

C Gamma waves have a higher frequency than radio waves.

D Gamma waves can travel further than radio waves.

b What determines the speed of an electromagnetic wave in a vacuum?

A Frequency

B Wavelength

C Energy

D All electromagnetic waves travel at the same speed in a vacuum.

c The frequency of an electromagnetic wave affects how much it is

- **A** absorbed by a given substance.
- **B** transmitted by a given substance.
- **C** reflected by a given substance.
- **D** All of the above.

Question

d Evaluate the statement that 'the gamma waves will reach the glass before the radio waves, but eventually all of the radio waves and gamma waves will reach the receiver'. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

List the following from highest energy to lowest energy.

X-rays, visible light, infrared, radio waves, gamma rays, microwaves, ultraviolet.

Question 7 (1 MARK)

List the following from longest to shortest wavelength.

X-rays, visible light, infrared, radio waves, gamma rays, microwaves, ultraviolet.

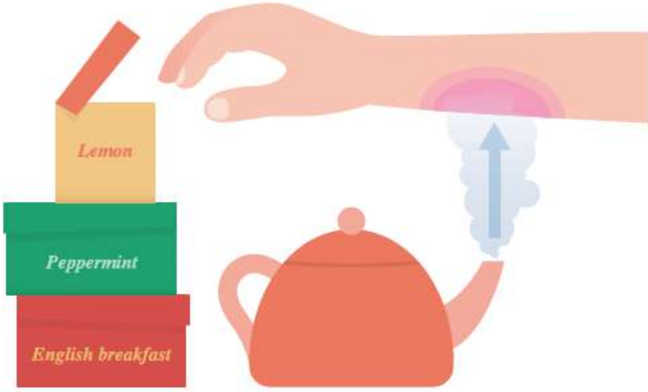
Question 8 (1 MARK)

When radiation from the Sun reaches the Earth's surface, it has to travel to the Earth's atmosphere and then through the atmosphere. Identify the property of electromagnetic waves that allows them to reach Earth's atmosphere from the Sun.

Previous lessons

Question 9 (7 MARKS)

Alice is boiling the kettle but makes the mistake of reaching over the spout of the kettle to reach the tea behind it. This causes her to scald her arm.



a Identify and explain the two heat transfers that moved energy from the hot steam in the pot to Alice's arm. (4 MARKS)

b A kettle provides 2.98×10^5 J of heat to 1.2 L of water. At the end of the process, the temperature of the water has increased by 50.0 K. Calculate the amount of energy the water transfers to its surroundings during the process. Take the heat capacity of water to be 4.2×10^3 J kg^{-1}. Assume the energy transfers into and out of the water are due to heat only (no work is done). (3 MARKS)

Key science skills

Question 10 (2 MARKS)

Students measure the wavelength of a red laser to be 658 nm. Express this wavelength in the appropriate SI unit to two significant figures.

3B THERMAL RADIATION

Lesson 2B established that radiation is one of the three forms of heat transfer. This lesson will focus on the relationship between temperature and the emission of radiation, including why objects glow when they are very hot and how we can use this principle to determine the temperature of the stars.

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot points

- describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared
- calculate the peak wavelength of the re-radiated electromagnetic radiation from Earth using Wien's Law: $\lambda_{max}T$ = constant
- compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures such as the Sun
- describe power radiated by a body as being dependent on the temperature of the body according to the Stefan-Boltzmann Law, $P \propto T^4$

Key knowledge units

Peak wavelength and Wien's Law	1.1.11.1
Radiative power and the Stefan-Boltzmann law	1.1.13.1
Electromagnetic spectrums of real bodies	1.1.10.1 & 1.1.12.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$\lambda_{max} = \frac{b}{T}$ Wien's Law
	$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$ Stefan-Boltzmann Law

Definitions for this lesson

black body an ideal body that absorbs (before re-emitting) all incoming electromagnetic radiation and does not transmit or reflect any of the radiation

emissivity a measure of how effectively an object emits radiation

peak wavelength the wavelength of the highest intensity electromagnetic wave released as thermal radiation

power the rate of change of energy with respect to time

Peak wavelength and Wien's Law 1.1.11.1

OVERVIEW

Thermal radiation is emitted from all objects that have a temperature above absolute zero (0 K). It is common to model objects as black bodies, which are ideal absorbers and emitters. Wien's Law relates the temperature of a black body to the wavelength it emits most intensely.

THEORY DETAILS

Thermal radiation occurs over the entire electromagnetic spectrum. However, a radiating body releases each type of radiation in different amounts. It is common to consider the radiation from ideal objects known as black bodies, since all the radiation coming from a black body must be emitted rather than reflected.

Black-body radiation

In the context of thermal radiation, a black body is an object that:

- absorbs all incoming radiation; it does not reflect or transmit any radiation.
- emits the maximum amount of thermal radiation possible; when a black body is in thermal equilibrium, it will re-emit **all** the radiation that it absorbs.

A black body is an idealised object – no real objects are black bodies, however, some objects have similar enough properties that it is helpful to model them as black bodies.

As shown in Figure 1, the reason that a dark-coloured object appears dark is because it absorbs most of the incoming visible radiation rather than reflecting or transmitting it. This is also the reason that a black car will be warmer than a white one on a sunny day. **How much an object absorbs, transmits, or reflects light depends on the wavelength of the light.** For example, clear glass transmits most visible light but it absorbs most infrared radiation. **An ideal black body absorbs all wavelengths of radiation** (**not just visible light**).

Image: Chawapon Wongchuen/Shutterstock.com

Figure 1 For a light coloured surface, most of the incoming (visible) radiation is reflected, which we see, but for a dark coloured surface, most of the incoming (visible) radiation is absorbed rather than reflected.

A black body has its name because of the property that it absorbs all incoming radiation. However, black bodies also **emit radiation** very well, which can make the name seem misleading. For example, the Sun is very bright because it emits so much electromagnetic radiation in the visible spectrum. It also absorbs most electromagnetic radiation that reaches it. For these reasons, it can be modelled as a black body. The similarity between the Sun and a black body is shown later in the lesson in Figure 8.

If a surface easily absorbs a wavelength, it will not easily reflect it. However, the surface will easily emit this wavelength. This also works the other way: a surface that easily reflects a wavelength is not going to easily absorb or emit it.

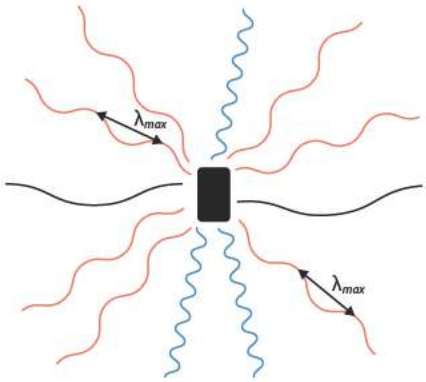


Figure 2 A body releasing thermal radiation. In this situation, the red waves are emitted with the maximum intensity (represented by the red waves outnumbering other waves). The wavelength of these is λ_{max}. The blue and black waves represent radiation from other parts of the electromagnetic spectrum.

Wien's Law

Wien's (pronounced *Veen's*) Law is a mathematical relationship between the temperature of a black body and the wavelength of light radiated with the **peak**, or maximum, intensity. This wavelength is also known as the peak wavelength.

$$\lambda_{max} = \frac{b}{T}$$

λ_{max} = peak wavelength (m), b = Wien's constant (2.898×10^{-3} m K), T = temperature (K)

Note that the units for Wien's constant are metres-kelvin, not millikelvin.

The equation shows that hotter objects emit a greater proportion of radiation with shorter wavelengths than colder objects. This can be seen in Figure 4. Also note that hotter objects emit more energy in total across the electromagnetic spectrum than colder objects.

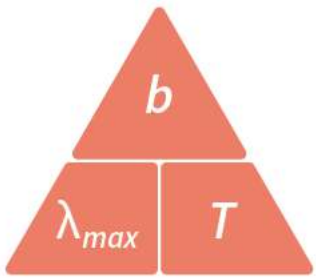


Figure 3 Formula triangle for Wien's law

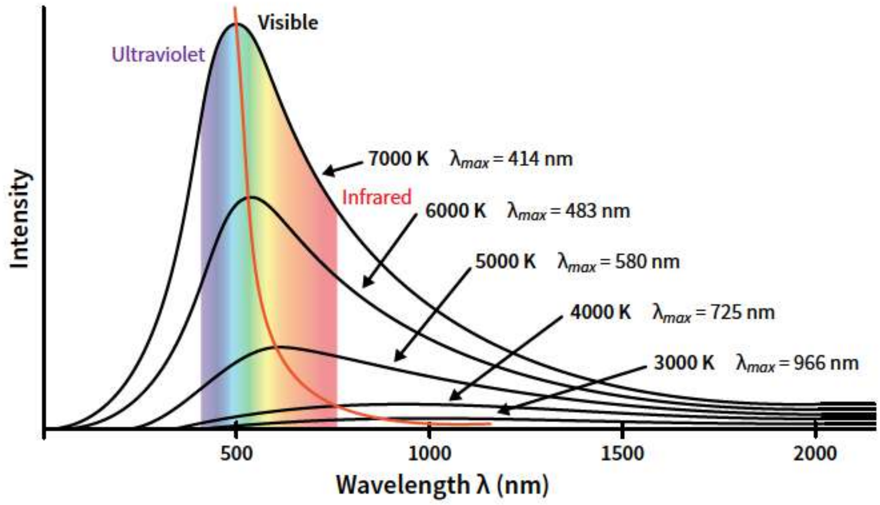


Figure 4 Each curve shows the intensities of the different wavelengths of light emitted by a black body at a given temperature. The red line passes through the peak intensity for each temperature.

Worked example 1

A piece of steel is heated up with a blowtorch until it is melting and "white hot". The steel is found to be at 3700 K. Find the peak wavelength for this temperature. Take $b = 2.898 \times 10^{-3}$ m K.

Working

$\lambda_{max} = \frac{b}{T} \therefore \lambda_{max} = \frac{2.898 \times 10^{-3}}{3700}$

$\lambda_{max} = 7.81 \times 10^{-7} = 781$ nm

Process of thinking

We have $T = 3700$ K and $b = 2.898 \times 10^{-3}$ m K.

Therefore we can use Wien's law: substitute in the values to find the peak wavelength.

Radiative power and the Stefan-Boltzmann Law 1.1.13.1

OVERVIEW

The power radiated by an object increases with the temperature of the object.

THEORY DETAILS

Hotter objects emit more power as electromagnetic radiation – across the entire electromagnetic spectrum – than colder objects. Power measures energy transfer per unit time. The SI unit for power is the watt (W), which is equal to one joule per second.

The Stefan-Boltzmann Law tells us that the total power emitted as thermal radiation for a given body is proportional to temperature to the fourth power.

$$P \propto T^4$$

The Stefan-Boltzman Law is useful for relating the radiative power of an object at two different temperatures. For this reason, the following formula can be a useful way of representing this relationship.

$$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$$

P_f = final power (W), P_i = initial power (W), T_f = final temperature (K), T_i = initial temperature (K)

For example:

- If the temperature of an object increases by a factor of two (doubles), the power radiated will increase by a factor of 16 (since $2^4 = 16$).
- If the temperature of a body increases by a factor of three (triples), the power radiated will increase by a factor of 81 (since $3^4 = 81$).

The full equation of the Stefan-Boltzmann law is not required knowledge according to the current VCE Physics Study Design but your class may choose to study it. The equation is:

$$P = A\varepsilon\sigma T^4$$

P = power (W), A = surface area of radiating body (m^2), ε = emissivity, σ = Stefan-Boltazmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T = temperature (K).

Emissivity defines how close to ideal any object is at emitting radiation.

- An emissivity of 1 ($\varepsilon = 1$) means that the body emits the maximum possible amount of thermal radiation. Such a body would be a black body.
- An emissivity of 0 ($\varepsilon = 0$) means that the body emits no thermal radiation.

All real objects have an emissivity between zero and one ($0 < \varepsilon < 1$).

Worked example 2

A piece of metal is heated from 400 K to 1600 K.

a **By what factor does the power it radiates increase due to the change in temperature?**

b **The metal radiates at a power of 2.5 W when its temperature is 400 K. Calculate the power radiated when the temperature reaches 1600 K.**

Working	Process of thinking
a $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$	As we are dealing with a change in temperature and its relationship to power we can use this relationship: $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$.
$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} = \frac{1600^4}{400^4} = 256$	Temperature increases by a factor of 4, so power increases by a factor of 4^4.
The power increases by a factor of 256.	Explicitly answer the question.
b $\frac{P_f}{P_i} = 256$	From part **a** increase in power is by a factor of 256.
$\therefore \frac{P_f}{2.5} = 256$ $P_f = 256 \times 2.5 = 6.4 \times 10^2$ W	We can substitute into this equation as shown.

Electromagnetic spectrums of real bodies 1.1.10.1 & 1.1.12.1

OVERVIEW

Any object with a temperature above absolute zero (0 K) emits thermal radiation at various frequencies. A hotter object emits each frequency with greater intensity than a colder object. A hotter object also emits a greater proportion of its total radiation as shorter wavelengths than colder objects emit.

THEORY DETAILS

The following section outlines the way that the total energy across the electromagnetic spectrum emitted by an object changes as the temperature increases.

For objects at temperatures below approximately 700 K, we cannot see the radiation they emit with our eyes. This is because they do not emit much radiation for each unit of surface area (compared with hotter objects) and their peak wavelength is in the infrared region. This means the vast majority of the small amount of radiation they emit has longer wavelengths than radiation in the visible spectrum.

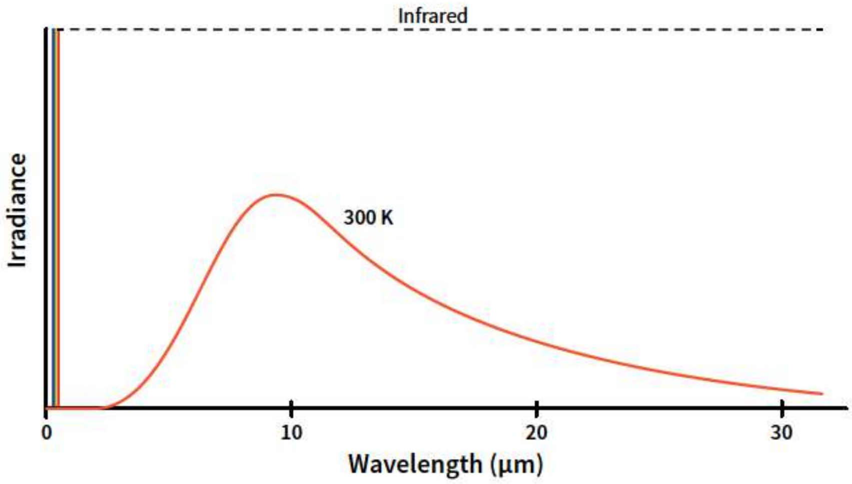


Figure 5 Black-body curve for an object at 300 K

Devices such as infrared cameras can detect the different wavelengths of the infrared spectrum released by objects at (and around) room temperature (see Figure 5).

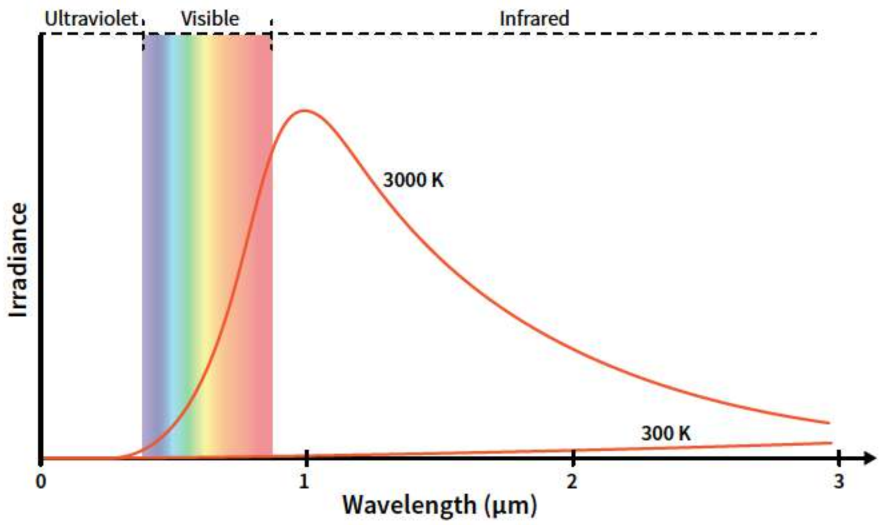


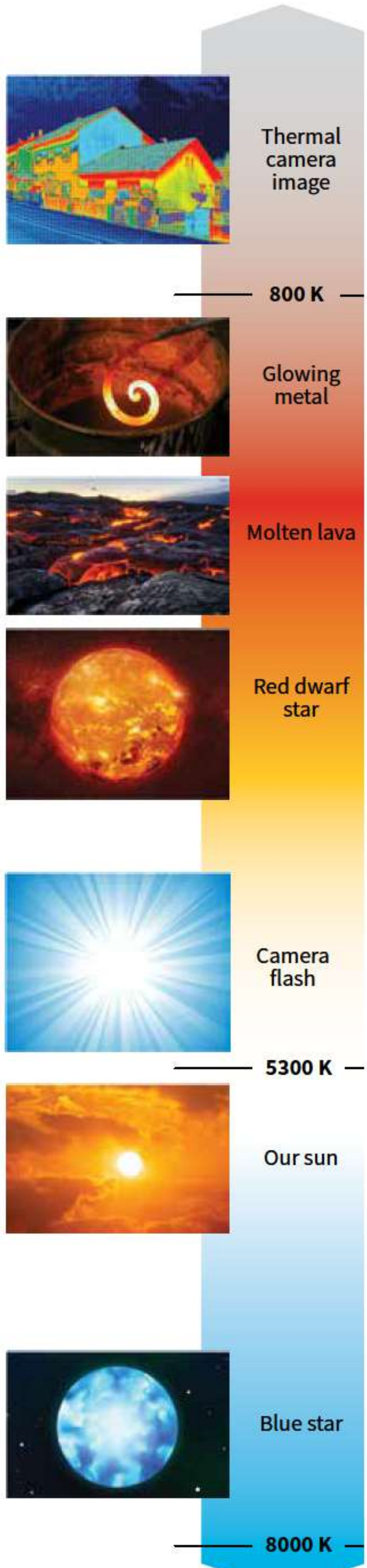
Figure 6 A comparison of the radiation emitted by black bodies at 300 K and 3000 K

Objects emit increasing amounts of radiation in the visible spectrum as the temperature increases. The perceived colour (the colour that we observe with our eyes) changes from red to yellow to white, and finally to blue. Notably, the perceived colour does not change through all the colours of a rainbow, as you might expect. This is because the colour that we perceive is our brains' interpretation of all the wavelengths the eye receives. For example, when the peak wavelength emitted by an object corresponds to a cyan colour, the object also emits a significant amount of the other wavelengths from the visible spectrum so we perceive the object as glowing white.

The Sun's surface is at a temperature of 5778 K, so it glows white (when viewed from outside our atmosphere). Hotter stars, such as Sirius and Vega, glow bluer. The hottest stars, which have surface temperatures above 7000 K, are more blue and the cooler ones, which have surface temperatures around 4000 K, are more red.

The Sun emits radiation mostly as infrared (~50%), visible light (~40%), and ultraviolet (~10%). These types of radiation have the following properties:

- Radiation from the visible part of the spectrum is generally better than infrared at penetrating (transmitting) through the Earth's atmosphere.
- The short wavelength (blue) end of the visible spectrum scatters as it passes through the atmosphere more than the long wavelength (red) end. This causes the sky to appear blue and the Sun to appear yellow on Earth.
- Ultraviolet radiation is mostly absorbed by the ozone layer around the Earth, but some reaches the surface.



Images (top to bottom): Ivan Smuk, Zyabich, Thijs Peters, Dotted Yeti, Artem Loskutnikov, Torychemistry, Veronika By/ Shutterstock.com

Figure 7 Colour temperature spectrum

Figure 8 compares the black-body curve for a body at 5578 K and the actual radiation the Sun releases.

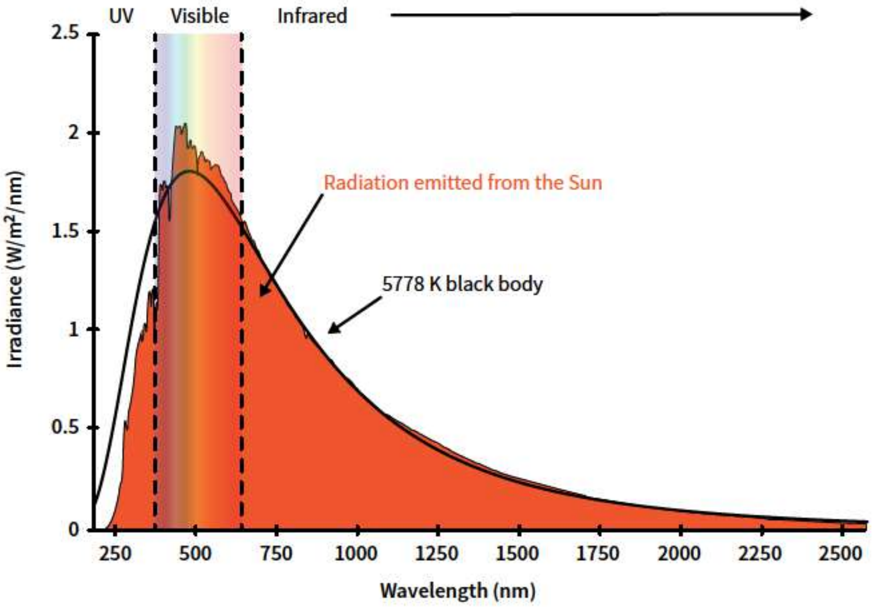


Figure 8 The radiation emitted by the Sun compared to an ideal black body at 5778 K (black line)

A hotter object emits a greater proportion of its radiation in shorter wavelengths but it also emits more radiation of every wavelength. This means that, even as the peak wavelength becomes shorter than the visible spectrum, the total amount of visible light emitted will increase as the object gets hotter.

Image: Zakharchuk/Shutterstock.com

Figure 9 Night sky with red, yellow, white, and blue stars – the possible colours of a black body

[redacted]

Theory summary

- All bodies radiate their heat as electromagnetic waves.
- A black body is an idealised object that absorbs all incoming electromagnetic radiation and emits the maximum possible radiation.
- Wien's Law is used to calculate the peak wavelength (the wavelength of maximum intensity) for a black body at any particular temperature.
  - $\lambda_{max} = \frac{b}{T}$, taking b as 2.898×10^{-3} m K
- The Stefan-Boltzmann Law states that the power (energy per second) radiated from a body is related to the temperature of that body.
  - $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$
- As the temperature of an object increases:
  - The total energy across the entire electromagnetic spectrum radiated per second by the object increases.
  - The proportion of radiation that is short wavelength (high frequency, high energy) increases.
- The Sun emits mostly infrared, visible, and ultraviolet light.

KEEN TO INVESTIGATE?

PhET 'Blackbody Spectrum' simulation
phet.colorado.edu/en/simulation/blackbody-spectrum

YouTube video: Daniel M – Blackbodies and Emissivity
youtu.be/HgRjXZV-kew

YouTube video: Physics Girl – Solving crimes with INFRARED?
youtu.be/1Un08ziq82Y

YouTube video: Veritasium – The World in UV
youtu.be/V9K6gjR07Po

The Concord Consortium Energy 2D simulation
energy.concord.org/energy2d/

CONCEPT DISCUSSION QUESTION

Kettles often have a shiny metallic surface on the outside. Discuss the reasons for this.

Answers on page 504

Image: DD Images/Shutterstock.com

Hints

Have you considered how shiny objects reflect, absorb, and emit radiation?

Have you considered the function of the kettle?

Have you considered energy transfers in the function of the kettle?

3B Questions

THEORY REVIEW QUESTIONS

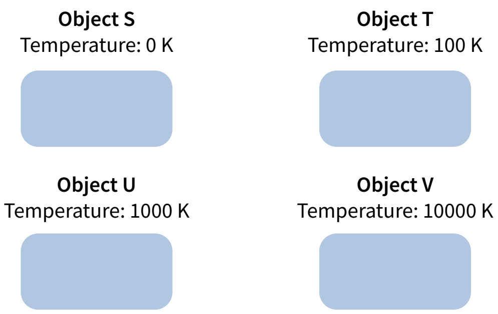
Question 1

A black body __________, __________, and __________.

A absorbs all incoming radiation, reflects no incoming radiation, has an emissivity of 1

B absorbs some radiation, emits all radiation, has an emissivity of 0

Use the following information to answer Questions 2 and 3.



Question 2

Which of the objects are releasing thermal radiation?

A U, V

B T, U, and V

C All of the objects

Question 3

Which of the objects has the longest peak wavelength?

A S

B T

C V

Question 4

Which of the following statements about a black body emitting a peak wavelength of 650 nm (which is in the visible spectrum) is true?

A It also emits wavelengths in the infrared and ultraviolet spectrums.

B All the thermal radiation it emits is visible.

Question 5

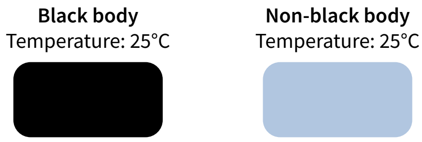
One object is glowing red due to thermal radiation and another is glowing blue due to thermal radiation. What can we conclude?

A The red object is hotter.

B The blue object is hotter.

Question 6

Two objects of similar size, shape and temperature have different abilities to emit. One can be closely modelled to be a black body and the other cannot.



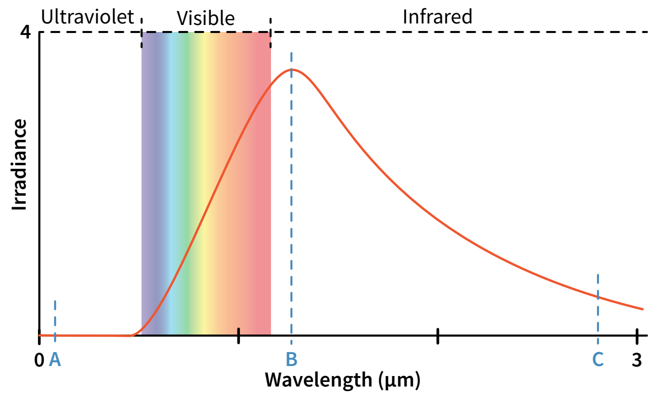
Which one is likely to release more energy as radiation?

A Black body

B Non-black body

Question 7

From the graph, identify which point on the horizontal axis (A, B, or C) represents the peak wavelength released by the object.



Question 8

Fill in the gaps in the following paragraph.

A blue star releases thermal radiation __________ (across the entire spectrum/as only blue light). The blue appearance of the star is created by the __________ (reflection of blue light/ predominance of blue light in the radiation).

Question 9

Rollo points an electromagnetic wave detector at the Sun. The detector picks up large amounts of infrared, visible light, and a moderate amount of ultraviolet radiation. Which is the best reason that he detects only very small amounts of light from the other parts of the spectrum?

A Even though the Sun produces a large amount of all types of electromagnetic radiation, the atmosphere absorbs most of the light that is not infrared, visible or ultraviolet.

B The Sun does not release other types of light.

C The other types of radiation are mostly absorbed by other celestial bodies like Mercury, Mars, Venus, and the Moon.

D The Sun mainly emits infrared, visible, and ultraviolet radiation.

Question 10

An object that has an initial temperature of 20°C is found to have increased its radiative power by a factor of 16 when its temperature doubles. This indicates that the final temperature of the object is:

A 40°C

B 313°C

DECONSTRUCTED EXAM-STYLE QUESTION

Question 11 (4 MARKS)

A lump of iron is placed into a fire in order to mould it into shape. It is initially at a temperature of 23.5°C and it radiates 33 W at this temperature. The blacksmith needs its surface to reach a certain temperature before she can start work on it but she forgot her thermometer. She does, however, have a wavelength detector and knows that the required peak wavelength is 3560 nm.

Take Wien's constant, b, to be 2.898×10^{-3} m K.

Prompts

a What is the most appropriate equation to use to calculate the required temperature given that the required peak wavelength is known?

A $\lambda_{max} = \frac{T}{b}$

B $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$

C $P = A\varepsilon\sigma T^4$

D $\lambda_{max} = \frac{b}{T}$

b What unit should be used for the wavelength in Wien's Law?

A hertz

B metres per second

C metres

D nanometres

c Which of the following is the most useful way to represent the initial temperature of the iron for the purposes of relating temperature to power radiated?

A 296.65 K

B 296.65°C

C 23.5 K

D 23.5°C

d Which formula should be used to calculate the radiative power at the required temperature given that the initial power, initial temperature, and final temperature are known?

A $P = \frac{b}{T}$

B $P = T^4$

C $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$

D $P = A\varepsilon\sigma T^4$

Question

e Calculate the power radiated after it has reached its final temperature. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 12 (2 MARKS)

Calculate the λ_{max} of a star with an average temperature of 7000 K. Take Wien's constant, b, to be 2.898×10^{-3} m K.

Question 13 (1 MARK)

A student measures the power radiated by a body to increase from 2.0 W to 512 W as its temperature increases. By what factor did the temperature increase?

A 2

B 3

C 4

D 5

Question 14 (4 MARKS)

Zayn is heating up a piece of metal. He finds, after a time, the metal changes colour from a "metallic silver" to a red, then orange, then bright white.

a The change in the metal's colour can be considered to occur in two stages:

- From "metallic silver" to red
- From red to orange to white

Explain the reasons for the colour change during these two stages, and describe how the intensity of light changes as the temperature increases. (2 MARKS)

b Zayn finds that the most intensely emitted wavelength while the metal melts is 680 nm. Find the melting point of the metal in kelvin. Take $b = 2.898 \times 10^{-3}$ m K. (2 MARKS)

Question 15 (5 MARKS)

A piece of glass has been heated to 1280°C and is glowing red.

a Calculate the λ_{max} for a black body at the same temperature as this piece of glass. Take Wien's constant b to be 2.898×10^{-3} m K. (2 MARKS)

b Explain why the piece of glass is glowing red even though its λ_{max} is not in the visible range of the spectrum. (3 MARKS)

Question 16 (3 MARKS)

Luna and Selene are having a discussion about the nature of the Moon's light. Luna claims that the bright light arriving on Earth from the Moon at night is evidence that the Moon must be acting like a black-body radiator. Selene disagrees.

Evaluate Luna and Selene's claims.

Question 17 (7 MARKS)

Suppose Xath is a distant star with the odd property that it rapidly changes temperature. At one extreme, Xath appears white with a blue tinge, with $\lambda_{max} = 405$ nm. At the other extreme, Xath appears much redder with $\lambda_{max} = 710$ nm.

Take Wien's constant b to be 2.898×10^{-3} m K

a Is Xath emitting less power when it appears white or red? Justify your answer. (2 MARKS)

b Calculate Xath's highest and lowest temperatures. (2 MARKS)

c Express the radiative power when Xath is at its minimum temperature as a percentage of the radiative power when Xath is at its maximum temperature (to the nearest percent). (3 MARKS)

Question 18 (7 MARKS)

Simran has a lamp in her room and it shines on her face as she studies. After some time, she notices a small amount of warmth from the lamp.

a The filament of the lamp starts at room temperature, 298 K, and reaches 2700 K. Considering the lamp emits 99 W of power when it is at its hottest, calculate the power emitted by the lamp at room temperature. (2 MARKS)

b Simran discovers that humans emit 1000 W of power. Considering a person has an average surface area of 2.00 m^2 and an average surface temperature of 35.2°C, calculate the emissivity of a person. Take the value of σ to be 5.67×10^{-8} W m^{-2} K^{-4}. (3 MARKS)

c Use your previous answer to comment on how well a black body could model a person. (2 MARKS)

Previous lessons

Question 19 (1 MARK)

Which of the following statements about electromagnetic waves is true?

A X-rays have longer wavelengths than waves in the ultraviolet region.

B The Sun releases mostly waves in the ultraviolet part of the spectrum.

C X-rays are more energetic (have more energy) than all other electromagnetic waves apart from gamma waves.

D Radio waves and infrared have the same frequency.

Question 20 (4 MARKS)

An unknown liquid is found to have a specific heat capacity of 6.3×10^3 J kg^{-1} K^{-1}.

a Calculate the energy it would take to increase the temperature of 1.2 kg of this liquid from 20°C to 40°C. (2 MARKS)

b The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. A kilogram of water and a kilogram of the unknown liquid are heated to 50.0°C and are left to cool. Assuming both release heat at the same rate, which do you expect to reach room temperature first? Explain your answer. (2 MARKS)

Key science skills

Question 21 (2 MARKS)

Stella and Asteri are taking measurements of the Sun's peak wavelength.

	Stella	Asteri
λ_1 (nm)	646	511
λ_2 (nm)	810	371
λ_3 (nm)	401	611
λ_4 (nm)	711	687
λ_5 (nm)	526	305
λ_6 (nm)	276	540
λ_{avg} (nm)	562	504

Compare the precision of Stella and Asteri's data.

3C EARTH'S ENERGY FLOW

Energy flows on Earth range from large scale convection in the mantle which is responsible for tectonic movement to smaller scale sea breezes that keep beaches cool on a hot day. The movement of energy around the Earth is the driving force behind geomorphic (processes that alter the Earth's surface) and meteorological (processes that relate to the weather and climate) activity.

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot point

- explain the roles of conduction, convection and radiation in moving heat around in Earth's mantle (tectonic movement) and atmosphere (weather)

Key knowledge units

Heat flow in Earth's mantle	1.1.14.1
Heat flow in Earth's atmosphere	1.1.14.2

No previous or new formulas for this lesson

Definitions for this lesson

atmosphere the layers of gases around a planet

core the dense, hot, molten centre of the Earth

crust the thin surface of the Earth made of solid mineral and rock

mantle a solid region under the surface of the Earth between the crust and the outer core

tectonic plate a large portion of the Earth's crust, also known as a lithospheric plate

Heat flow in Earth's mantle 1.1.14.1

OVERVIEW

Convection currents of rock in the Earth's mantle, which are driven by heat from the Earth's core, move tectonic plates on the surface.

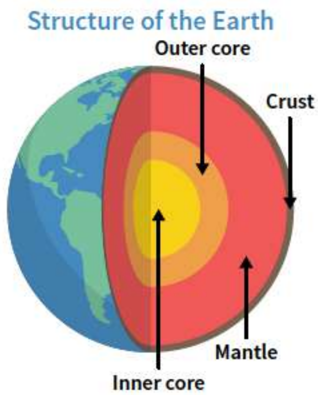


Figure 1 The internal structure of the Earth

THEORY DETAILS

We have all seen pictures of active volcanoes and observed the immense power of earthquakes on the news. These intense natural events are the result of the movement of energy (in the form of heat) in the layer of the Earth called the mantle (see Figure 1). The mantle is made of rock. It mainly behaves as a solid but when considered over geologic periods of time it flows like a thick fluid.

The mantle is hot (between 200°C at the crust and 4000°C at the outer core) and makes up the majority of the volume of the Earth. Due to the uneven temperature distribution in the mantle, convection currents form within it. Pillars of warmer rock move up towards the crust and displace the cooler rock close to the surface. As this rock gives its energy to the crust, it cools, becomes more dense, and returns to the bottom (see Figure 2).

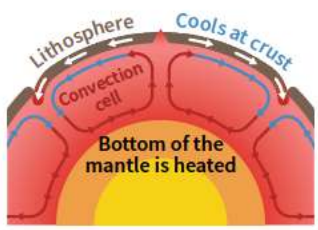


Figure 2 Cross section of convection cells in the mantle

The convection cells in the mantle closely resemble those formed by a rolling boil in a pot or the convection that occurs in a modern oven. Convection is normally limited to fluids (gases and liquids) but due to the intense heat and pressure in the mantle, convection of solid rock can occur. However, the convection currents in the mantle are very slow. They are often called "mantle creep".

The movement of the upper mantle causes the movements of tectonic plates that are ultimately responsible for volcanoes, earthquakes, and the creation of mountain ranges.

Heat flow in Earth's atmosphere 1.1.14.2

OVERVIEW

Radiation, conduction, and convection operate in Earth's atmosphere and have large impacts on weather and climate.

THEORY DETAILS

Radiation in the atmosphere

The Sun's radiation increases the temperature of the Earth's surface and the atmosphere but does so unevenly. The uneven distribution of this radiation is the primary driving force of convection currents above the Earth's surface (see Figure 3).

The uneven distribution of radiation is a result of the changing angle of the Earth's surface relative to the Sun's radiation, which means that the radiation is spread over a greater area towards the poles. This causes a decrease in average temperature towards the poles.

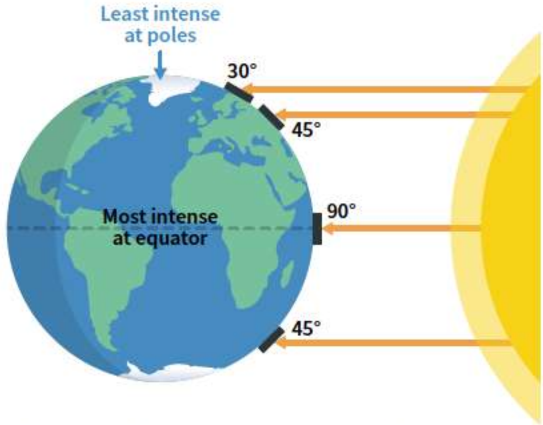


Figure 3 The Sun's radiation is most direct at the equator and least direct at the poles which causes uneven heating of the Earth's surface.

Conduction in the atmosphere

The atmosphere, ocean, and land exchange energy due to conduction. This occurs on both a global and local scale.

- On a global scale, in areas with more direct radiation such as equatorial regions (as shown in Figure 3) the land conducts heat to the air above it, causing the air to rise. In cooler regions, this happens to a much smaller extent.
- On a local scale, the land can be warmer than the air and the ocean may be cooler, or vice versa depending on the time of day.

These conduction processes drive atmospheric convection by heating the air through contact with the water or land.

Convection in the atmosphere

Convection in the atmosphere, just like in the mantle, occurs in cells. This convection is a result of the uneven distribution of radiation from the Sun that causes uneven conduction from the land and ocean to the air. This combination of radiation and conduction drives the convection cells that are responsible for much of our major climatic regions (such as tropical, desert, and temperate climates).

There are three convection cells between the equator and each pole (see Figure 4). These are the Hadley, Ferrel, and Polar cells. To understand how they work, we will focus on the Hadley cell (see Figure 5).

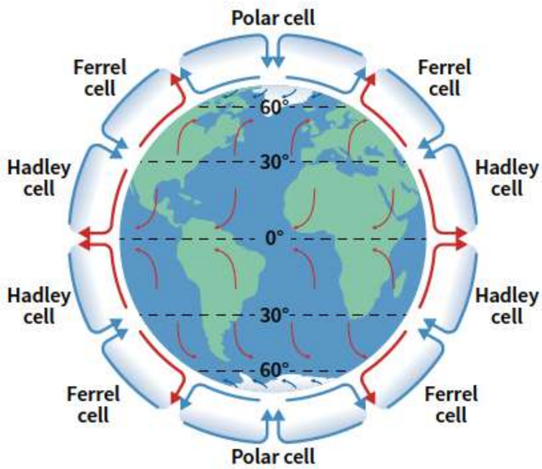


Figure 4 Global system of atmospheric convection cells

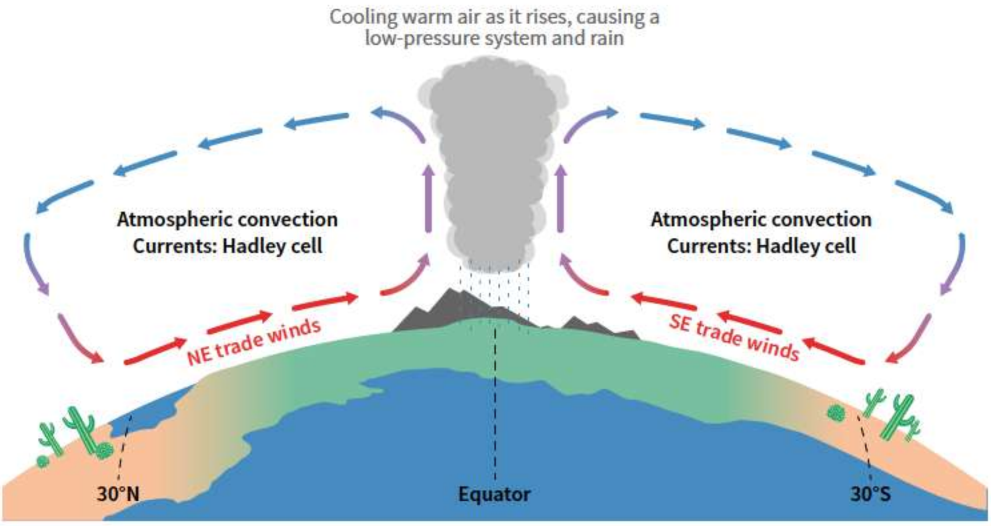


Figure 5 The Hadley cells north and south of the equator

The Hadley cell is warmed by the increased temperatures at the equator. This warm air is less dense so is replaced by cooler air. This rising air causes a low pressure system around the equator. As the warm air rises and moves away from the equator, it cools. Eventually, the air cools and becomes dense enough to fall back down to the surface of the Earth. The falling air forms a high pressure system.

Air moves from regions of high pressure to regions of low pressure causing winds called the 'trade winds' or 'easterlies'. These permanent east-to-west winds near the equator are driven by the Hadley cell but they are directed by the Coriolis effect, which is a consequence of the Earth's rotation.

The rising air near the equator also carries a lot of moisture due to evaporation over the oceans. As this air rises and cools, the moisture condenses which creates a lot of rain. By the time the air sinks in the cooler regions, it has very little moisture left. These convection cells are responsible for the bands of green rainforest and tropical climates around the equator and the bands of yellow desert at 30°N (30° north of the equator) and 30°S (see Figure 6).

Image: BlueRingMedia/Shutterstock.com

Figure 6 30°N and 30°S are associated with world deserts and the equator is associated with rainforest due to Hadley cells.

Due to local variations in conduction, convection currents also cause local weather patterns such as onshore winds (which blow from the ocean towards the land) and offshore winds (which blow from the land towards the ocean). Water has a higher specific heat capacity than land, which means the ocean's temperature is relatively stable. The land, on the other hand, has a greater variation in temperature between daytime and nighttime. Surfers often like to surf in the morning before the onshore winds form due to the rising temperature of the land.

Table 1 The causes of offshore and onshore winds

During the day – Figure 7(a)	During the night – Figure 7(b)
• The land is warmer than the ocean.	• The ocean is warmer than the land.
• Air above the warm land heats up and rises.	• Air above the warm sea heats up and rises.
• As the air moves over the cooler ocean it cools.	• As the air moves over the cooler land it cools.
• When it cools, it falls towards the ocean.	• When it cools, it falls towards the land.
• The air flows from the ocean onto the land due to the pressure difference.	• The air flows from the land to the ocean due to the pressure difference.
• This results in a **sea breeze** or **onshore wind**.	• This results in a **land breeze** or **offshore wind**.

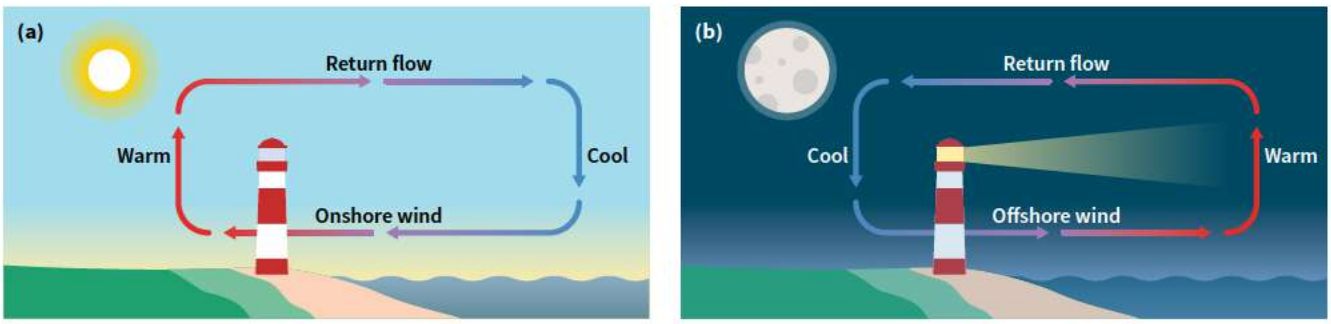


Figure 7 The convection currents responsible for **(a)** onshore winds during the day and **(b)** offshore winds during the night

Convection in the ocean

Convection currents in the ocean have a large impact on the global climate since they move thermal energy around the Earth. They are also the result of the imbalance of radiation from the Sun as the water at the equator is warmed much more than water close to the poles (see Figure 8).

Gyres (ocean currents moving around the surfaces of the Earth's major oceans) and other warm surface currents such as the Gulf Stream are driven by a combination of wind and the rotation of the Earth. These winds are driven by the Hadley, Ferrel, and Polar cells discussed above.

Other currents, such as the North Atlantic current, are driven by a combination of temperature and salinity. Salinity has large effects on density which causes warm currents to sink and then cool.

The warm or cool water these currents move is often responsible for local weather, the formation of hurricanes, cyclones, monsoons, and the nutrient content of oceans.

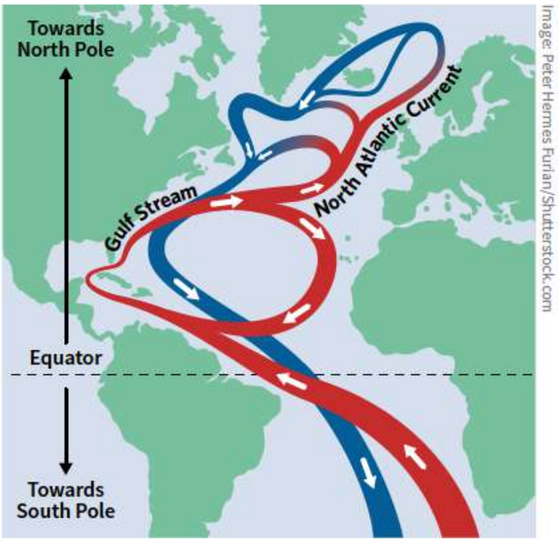


Figure 8 Connecting currents (the global conveyor belt) move thermal energy from the equator around the world and mix water from nearly all the Earth's major oceans.

Theory summary

- In the Earth's mantle, convection cells of slowly moving rock drive geomorphic activity on the surface.
- In the atmosphere:
  - Radiation from the Sun is responsible for the majority of Earth's warmth but is unevenly distributed over the Earth's surface.
  - Conduction between the land, ocean, and atmosphere is responsible for driving convection cells, such as onshore and offshore winds.
  - Convection cells occur:
    - in the atmosphere. These are responsible for some of our climate patterns.
    - in the ocean. These are responsible for some of our weather and moving nutrients around the ocean.

KEEN TO INVESTIGATE?

PennState University 'Atmospheric Convection: Hadley Cells'
e-education.psu.edu/earth111/node/752

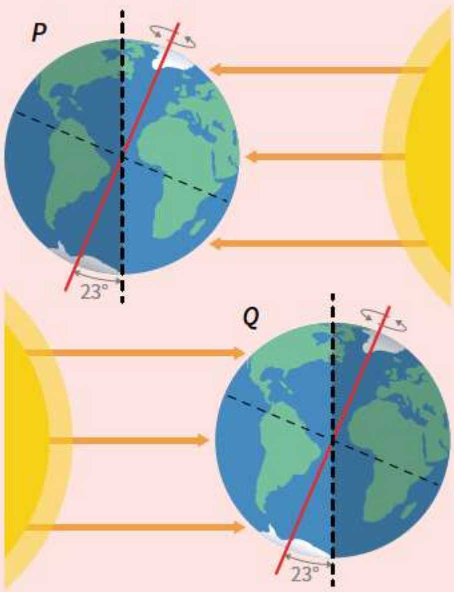
YouTube video: Kurzgesagt – In a Nutshell – The Gulf Stream Explained
youtu.be/UuGrBhK2c7U

CONCEPT DISCUSSION QUESTION

The Earth's axis has a 23° tilt relative to the sunlight. The diagrams represent opposite sides of the Earth's orbit around the Sun. Due to this tilt and the movement of the Earth around the Sun, different places on the Earth's surface get varying amounts of radiation depending on the time of year.

Discuss which diagram, *P* or *Q*, represents summer in Australia and how this system explains that in both spring and autumn, the Northern and Southern Hemispheres have similar temperatures.

Answers on page 504



Hints

Which diagram depicts the Southern Hemisphere as more exposed to the Sun?

Is there a time when one hemisphere is receiving more direct radiation than the other and how does this impact its average temperature?

Is there a time when neither the Northern Hemisphere nor the Southern Hemisphere would be receiving more direct radiation than the other and how does this impact its average temperature?

3C Questions

THEORY REVIEW QUESTIONS

Question 1

Convection cells in nature are caused by

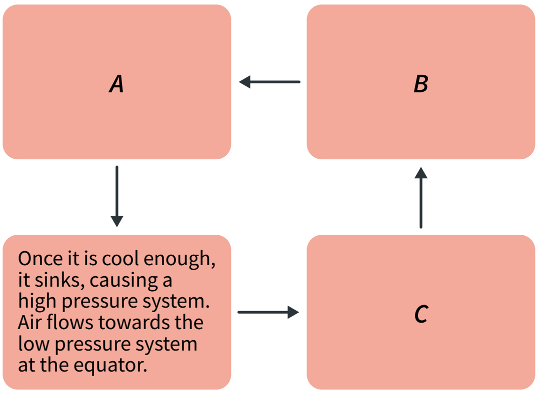
A an even distribution of heat provided.

B an imbalance in heat provided.

Question 2

Match the stages of the flowchart to the descriptions of the stages of the Hadley cell.

Flowchart



Stages of the Hadley cell

I Air at the equator is warmed by the land and water.

II Warm air loses its energy to the atmosphere and cools.

III Warm air rises as it is less dense causing a low pressure system.

Question 3

"Regardless of the fact that the mantle is solid, convection occurs."

Is the above statement true or false?

A True, the mantle behaves like a fluid over geologic time periods.

B False, the mantle cannot convect.

Question 4

Considering an onshore wind blows from the sea to the land and an offshore wind blows from the land to the sea, fill in the gaps in the following sentences.

In situations where the sea is warmer than the land, an __________ (onshore/offshore) wind is produced. In situations where the land is warmer than the sea, an __________ (onshore/offshore) wind is produced.

Question 5

On a hot day at the beach the wind from the ocean will be

A cooler than the land.

B warmer than the land.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 6 (3 MARKS)

The average temperature decreases as we move away from the equator.

Prompts

a The equator is warmer than the south pole due to

- **A** conduction.
- **B** convection.
- **C** ocean currents carrying the warmth from the south to the equator.
- **D** radiation from the Sun.

b The curvature of the Earth means that as you move north or south from the equator,

- **A** the intensity of the Sun's radiation decreases.
- **B** the intensity of the Sun's radiation increases.
- **C** the Earth has more water which means that it absorbs greater amounts of energy from the atmosphere due to its high heat capacity.
- **D** there is more cloud cover which reflects more incoming radiation causing the temperature to drop.

Question

c Explain one reason why the average temperature decreases as we move away from the equator. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 7 (1 MARK)

Convection is normally reserved for fluids but the solid rock in the mantle also undergoes convection. Identify which reason best explains the convection in the mantle.

A The tectonic plates that make up the Earth's crust move due to ocean currents and pull the rock at the surface of the mantle, which makes room for the other rocks to move up.

B The heat melts the stone which allows it to move.

C The intense heat and pressure allows solids to convect very slowly in the Earth's mantle.

D The convection cells are of the water within the rock's in the mantle, not the rock itself.

Question 8 (3 MARKS)

Identify the uneven heating causing these convection cells.

a A Hadley cell. (1 MARK)

b The South Pacific Gyre. (1 MARK)

c An offshore wind. (1 MARK)

Question 9 (2 MARKS)

Which energy transfer method warms the air just above the land and water at the equator? Explain your answer.

Question 10 (2 MARKS)

Which energy transfer method warms the land and water at the equator? Explain your answer.

Question 11 (3 MARKS)

Explain the production of onshore winds with reference to the energy transfers involved.

Question 12 (3 MARKS)

Water has a much higher specific heat capacity than the elements that make up the land. This means that the land cools and warms quicker than the water. During winter, coastal areas tend to be warmer than those inland. During the summer, coastal areas tend to be cooler than inland areas.

Explain how conduction contributes to coastal areas having more moderate temperatures than inland areas.

Previous lessons

Question 13 (3 MARKS)

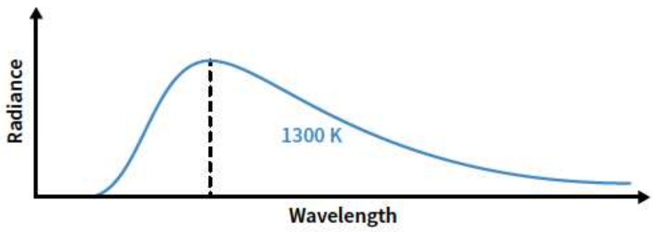
0.70 kg of ice at 0°C is added to 5.2 kg of water at 23.0°C in a thermally insulated container. The specific heat capacity of water is $c_w = 4.2 \times 10^3\ \text{J kg}^{-1}\ \text{K}^{-1}$ and the latent heat of fusion for ice to water is $L_f = 3.34 \times 10^5\ \text{J kg}^{-1}$.

a How much thermal energy is required to melt the ice? (1 MARK)

b How much energy is lost by the water originally around the ice cube if the final temperature of the water (including the melted ice) is 10.8°C? (2 MARKS)

Question 14 (6 MARKS)

The graph shows the radiance curve for an ideal black body at 1300 K.



a Copy the graph including the radiance curve and draw the resulting curve for a body at 1900 K. (1 MARK)

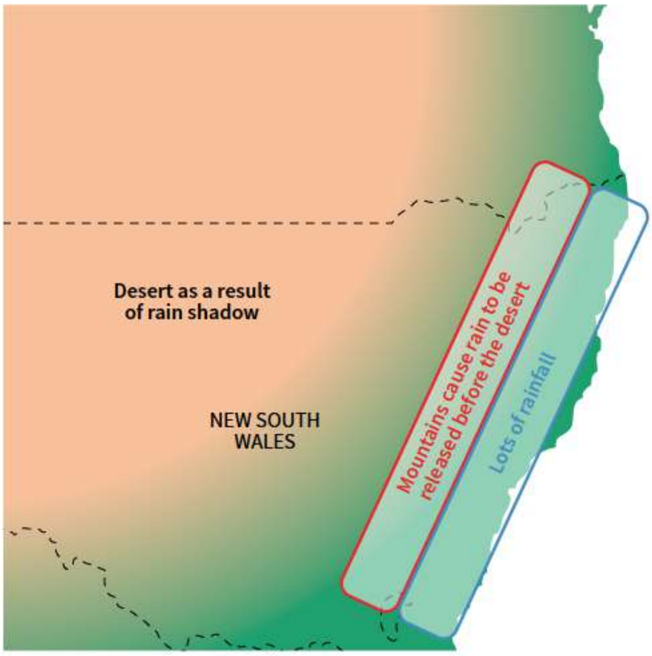
b Calculate the peak wavelength for the body at 1300 K. Take Wien's constant b to be 2.898×10^{-3} m K. (2 MARKS)

c The black body has a surface area of 1.39 m^2. Calculate the difference in power released at 1300 K and 1900 K using the equation $P = A\varepsilon\sigma\left(T_f^{\,4} - T_i^{\,4}\right)$ and taking the value of σ to be $5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$. (3 MARKS)

Key science skills

Question 15 (7 MARKS)

A phenomenon called the rain shadow effect occurs in coastal areas near mountain ranges, for example on the East coast of Australia before between the coast and the Great Dividing Range. The rain shadow effect causes a significant amount of rain on the coastal side of the mountain range and a lack of rain on the land side of the mountain range.



A student wants to test the rain shadow effect. They live on the mountain range near the coast so they place an identical rain gauge on either side of the mountain in a secure location. Over the next month the area receives substantial rain. When they return to the gauges, there is no substantial difference in the amount of water collected.

a Identify an independent, dependent, and controlled variable in this experiment. (3 MARKS)

b The rain shadow occurring where this student lives is not observable over such a short time period.

Explain two changes to the experimental method such that they have a better chance of observing the rain shadow effect. (4 MARKS)

3D THE GREENHOUSE EFFECT

Think about the Earth without its atmosphere. This rocky planet would probably resemble the Moon: cold and without life. The atmosphere is responsible not just for the air we breathe but keeping the warmth of the Sun contained. This lesson explores the details of how the atmosphere retains the energy that the Sun provides.

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot points

- model the greenhouse effect as the flow and retention of thermal energy from the Sun, Earth's surface and Earth's atmosphere
- explain how greenhouse gases in the atmosphere (including methane, water and carbon dioxide) absorb and re-emit infrared radiation

Key knowledge units

Earth's energy budget	1.1.15.1
The greenhouse effect	1.1.15.2
Greenhouse gases	1.1.16.1

No previous or new formulas for this lesson

Definitions for this lesson

greenhouse effect the trapping of thermal radiation emitted from the Earth by greenhouse gases in the atmosphere, keeping the Earth's temperature higher than it would otherwise be

greenhouse gas a gas that is better at absorbing radiation emitted by the Earth than radiation emitted by the Sun

Earth's energy budget 1.1.15.1

OVERVIEW

For the Earth's temperature to remain constant, incoming solar radiation must be balanced by the Earth's outgoing radiation. The average temperatures we experience are maintained by the energy contained within the atmosphere.

THEORY DETAILS

The Earth's temperature depends on how much radiation from the Sun is let in, how much is retained by the atmosphere, and how much is let out by the atmosphere back into space. These quantities of incoming, retained, and outgoing radiation are the major factors in Earth's energy budget.

Energy from the Sun

The Earth receives essentially all of its energy from the Sun's thermal radiation. We remember from Lesson 3B that this is mainly in the infrared, visible, and ultraviolet parts of the electromagnetic spectrum. Most of this radiation is of a shorter wavelength than most radiation emitted by the Earth (so it is sometimes referred to as shortwave radiation, whilst radiation from the Earth is sometimes referred to as longwave radiation).

Radiation from the Sun is either absorbed, transmitted, or reflected by the atmosphere, clouds, and the Earth's surface. Around 70% of incoming solar radiation contributes to Earth's temperature by being absorbed and the rest is reflected back to space. Most of the absorption occurs at the surface because the atmosphere mostly transmits solar radiation. See Figure 1.

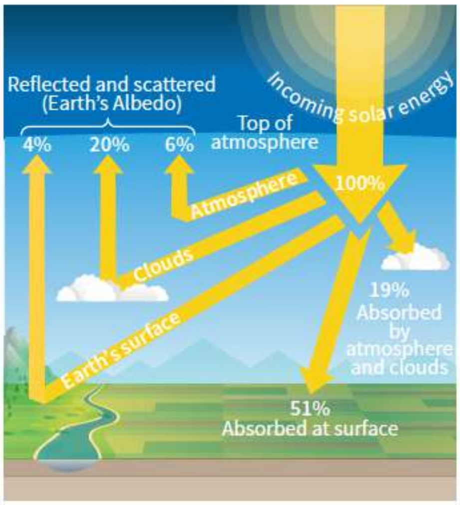


Image: VectorMine/Shutterstock.com

Figure 1 The energy from the Sun that is absorbed and reflected by the Earth

Energy from the Earth

In Lesson 3B we learned that the peak wavelength that a black body emits is inversely proportional to its surface temperature. So the Earth emits relatively long wavelength radiation, almost entirely in the infrared region, when compared to the much hotter Sun.

As seen in Figure 2, only a small amount of the radiation that leaves the Earth's surface transmits directly to space. The rest of the energy is absorbed by the atmosphere or clouds before being re-emitted.

Because this energy stays in the atmosphere for a long time, it preserves the temperature of the Earth. Radiation from the Sun provides heat to the Earth and its atmosphere and much of the warmth is retained by the atmosphere absorbing radiation emitted from the Earth. This is called the greenhouse effect.

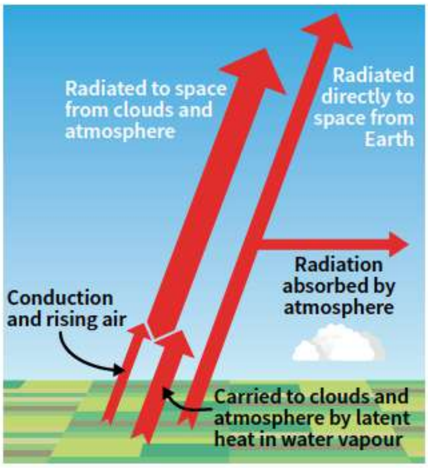


Image: VectorMine/Shutterstock.com

Figure 2 The radiation emitted by the Earth and what happens to it

The greenhouse effect 1.1.15.2

OVERVIEW

The natural process in which the Earth's radiation in the atmosphere is absorbed and emitted by particular gases is called the greenhouse effect. This retains energy in our atmosphere.

THEORY DETAILS

The greenhouse effect is named after a greenhouse you may find in a garden (see Figure 3). Greenhouses trap heat and increase the temperature inside. Solar radiation is transmitted through the glass and it is subsequently absorbed by the ground, plants, and other objects inside. Energy is re-emitted by the Earth or ground as almost entirely infrared radiation, which is more likely to be reflected or absorbed by the greenhouse. This retains energy inside the 'atmosphere' of the greenhouse.

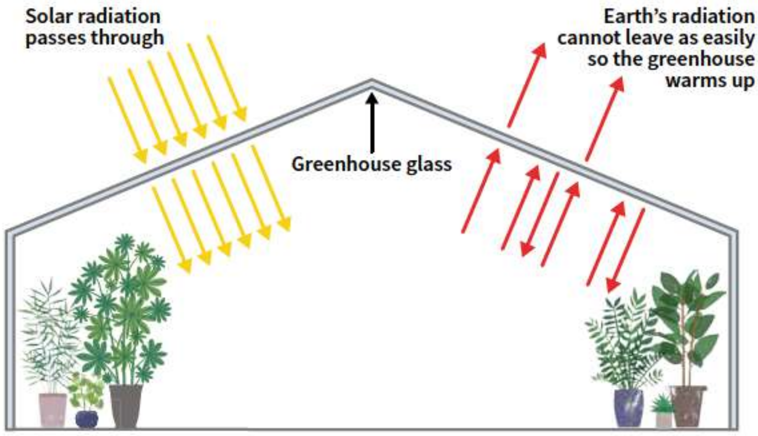


Image: GoodStudio/Shutterstock.com

Figure 3 The function of a greenhouse

This greenhouse, after being installed, will eventually reach a constant temperature. This is a result of the balance between incoming solar radiation and outgoing infrared radiation.

Just as the glass in the greenhouse acts to let certain radiation in and prevent some radiation escaping, so does our atmosphere (see Figure 4). The temperature of the Earth is similarly a result of the same balance of retention, incoming radiation, and outgoing radiation.

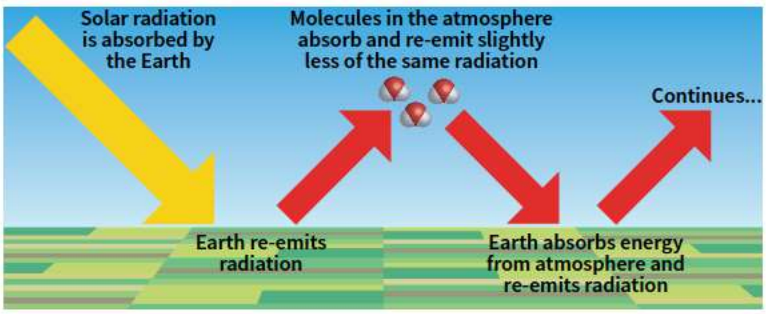


Figure 4 The greenhouse effect

The greenhouse effect is a vital natural process. Without the greenhouse effect, the Earth's average temperature would be –18°C instead of 15°C. Without this temperature increase there would be no way that life as we know it could develop on Earth.

Greenhouse gases 1.1.16.1

OVERVIEW

Greenhouses gases are particularly good at absorbing the Earth's radiation due to their atomic structure.

THEORY DETAILS

Greenhouse gases are a set of gases in our atmosphere that have a strong ability to absorb Earth's radiation and are responsible for the greenhouse effect. Some of the most important, naturally occurring greenhouse gases are:

- Carbon dioxide (CO_2)
- Methane (NH_4)
- Water vapour (H_2O).

Their ability to absorb Earth's radiation comes from their structure. As they consist of three or more atoms, they can vibrate at a different range of frequencies to oxygen (O_2) or nitrogen (N_2) which make up most of the Earth's atmosphere. The frequencies absorbed by the greenhouse gases correspond to the infrared frequencies of radiation emitted by the Earth. This means that they absorb the Earth's radiation well but solar radiation is much better transmitted (see Figure 5).

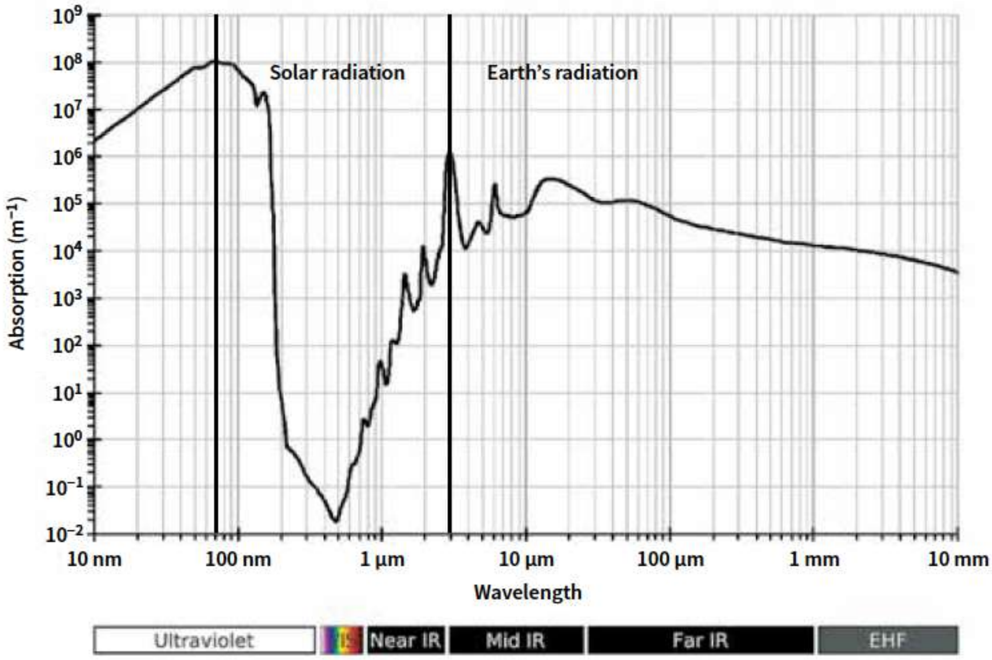


Figure 5 The absorption spectrum of water. The water vapour in the atmosphere is effective at absorbing Earth's radiation (almost entirely mid- or far-infrared radiation) but is poor at absorbing solar radiation (mainly ultraviolet, visible and near-infrared radiation).

Theory summary

- The Earth is constantly receiving and emitting radiation in a delicate balance.
  - It receives the majority of its energy as radiation from the Sun.
  - The majority of the energy that it loses escapes from the atmosphere as infrared radiation.
  - It retains some of this energy due to the greenhouse effect.
- The greenhouse effect describes how some molecules (greenhouses gases) trap energy by absorbing and re-emitting Earth's radiation.
  - This warms our atmosphere by 33°C.
- The main greenhouse gases are carbon dioxide, water vapour, and methane, which absorb and emit radiation in the infrared spectrum.

KEEN TO INVESTIGATE?

PhET 'Greenhouse Effect' simulation
phet.colorado.edu/en/simulation/legacy/greenhouse

YouTube video: California Academy of Science – Earth's Delicate Energy Balance
youtu.be/U2CPwWgY_G4

CONCEPT DISCUSSION QUESTION

Imagine that suddenly the surface temperature of the Sun increases by a significant factor and starts to release much more energy. This energy would increase Earth's temperature but how long would it take? Discuss factors that might slow or speed up the time it would take for the Earth to increase in temperature.

Answers on page 504

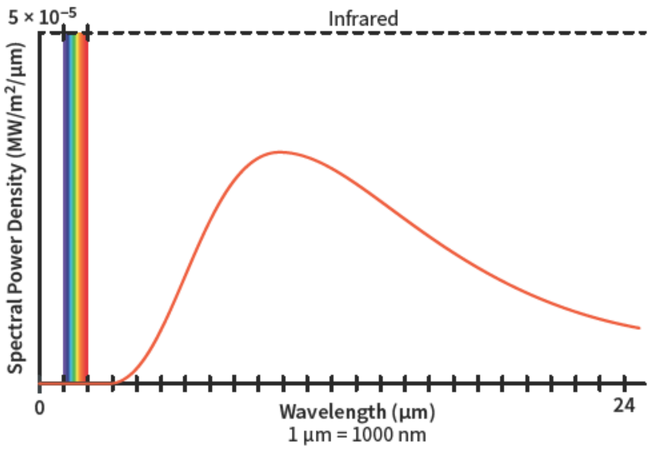
Hints
How does the radiation of the Sun impact Earth's temperature?
How does the Earth retain its temperature?

3D Questions

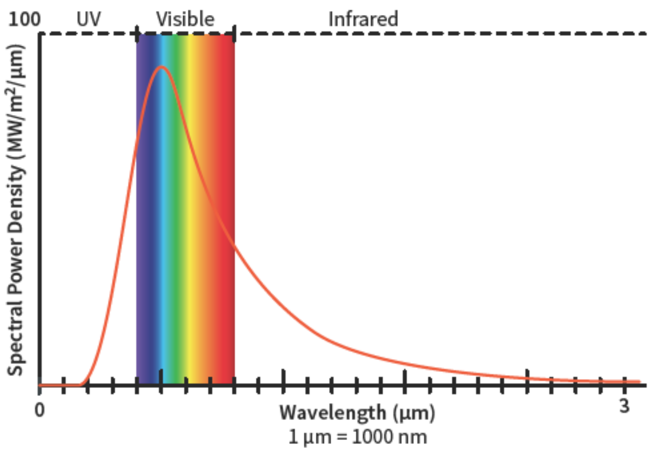
THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–9.

Spectrum *P*



Spectrum *Q*



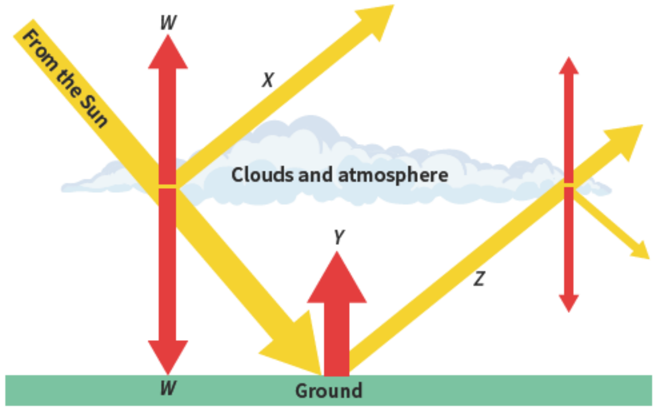


Image: vectortatu/Shutterstock.com

Question 1

Identify which spectrum, *P* or *Q*, better represents the radiation spectrum of the Sun and which spectrum better represents the radiation spectrum of the Earth.

Question 2

Whenever radiation interacts with matter, including the atmosphere or the ground, some of the radiation will be __________ (reflected/convected), some will be __________ (conducted/absorbed), and the rest will be __________ (enhanced (becomes more intense)/transmitted).

Question 3

The proportion of radiation that undergoes each of the three processes from the previous question

A is always the same.

B depends on the material but not the wavelength of the radiation.

C depends on the wavelength of the radiation but not the material.

D depends on both the material and the wavelength of the radiation.

Question 4

When radiation is absorbed by matter, the matter gets hotter and emits its own radiation

A with the same distribution of wavelengths that is absorbed.

B with a distribution of wavelengths that depends on the temperature of the matter.

Question 5

Reflected radiation has

A a distribution of wavelengths that depends on the spectrum of incident light.

B a distribution of wavelengths that depends on the temperature of the matter.

Question 6

The *X* and *Z* arrows represent reflected radiation with a spectrum that is better represented by spectrum __________ (*P*/*Q*).

Question 7

The *W* arrows represent radiation that has been __________ (absorbed/emitted) by the atmosphere as a result of absorbing some of the Sun's radiation and getting hotter. The spectrum of this radiation is better represented by __________ (*P*/*Q*).

Question 8

Much of the radiation represented by arrow *Z* passes through the atmosphere into space. Most of the radiation represented by arrow *Y* does not pass through the atmosphere. The reason for this difference is that greenhouse gases absorb a large proportion of the __________ (longer (infrared)/shorter) wavelengths but they allow __________ (longer (infrared)/ shorter) wavelengths to transmit.

Question 9

An increase in the amount of greenhouse gas in the atmosphere causes

A an increase in the amount of radiation represented by arrow *Y* that is trapped by being absorbed (and a decrease in the amount of arrow *Y* that transmits through to space).

B an increase in the amount of radiation reaching the Earth from the Sun.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 10 (3 MARKS)

The Earth and the Sun are in a relationship called radiative equilibrium. This is achieved when the temperature of both bodies are relatively static even though the Earth is still receiving the Sun's radiation.

Prompts

a Which of the following best describes the Earth's incoming radiation in terms of its source and its wavelength?

A Shorter wavelength radiation from the Earth

B Longer wavelength radiation from the Earth

C Shorter wavelength radiation from the Sun

D Longer wavelength radiation from the Sun

b Which of the following best describes the Earth's outgoing radiation in terms of its source and its wavelength?

A Shorter wavelength radiation from the Earth

B Longer wavelength radiation from the Earth

C Shorter wavelength radiation from the Sun

D Longer wavelength radiation from the Sun

c Which of the following are other ways radiation is retained or otherwise disrupted on its way into or out of the Earth's atmosphere?

A Reflected by clouds

B Reflected by the atmosphere

C Absorbed by the atmosphere

D All of the above

Question

d Explain the temperature balance that the Earth reaches with the Sun. There is no need to address specific temperatures. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 11 (1 MARK)

Identify the name of the process that retains thermal energy in the Earth's atmosphere.

A Geothermal warming

B Greenhouse effect

C Infrared radiation

D Solar radiation

Question 12 (4 MARKS)

a Identify which part of the electromagnetic spectrum makes up most of both solar radiation and Earth's radiation and explain how this part of the spectrum is different between the two types of radiation. (2 MARKS)

b Name three common greenhouse gases. (2 MARKS)

Question 13 (3 MARKS)

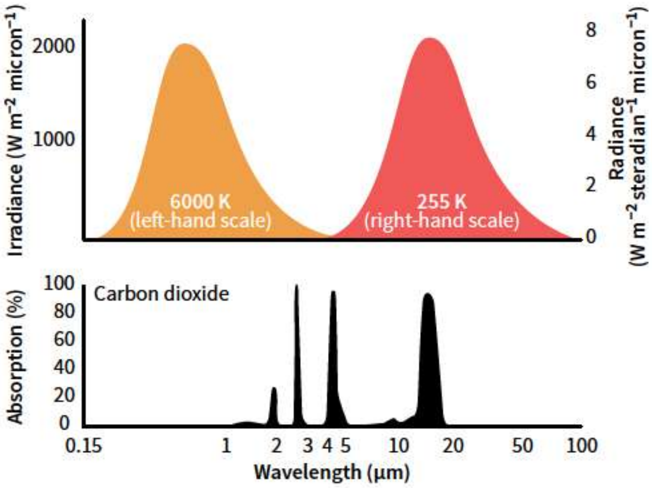
Of the energy that the Earth emits as radiation, only 5% of it directly escapes into space.

a Explain what happens to the remaining 95%. (2 MARKS)

b In what region of the electromagnetic spectrum is the emitted radiation? (1 MARK)

Question 14 (3 MARKS)

Explain why carbon dioxide in the Earth's atmosphere absorbs and emits the re-radiated heat from the Earth much more effectively than it absorbs and emits the Sun's incoming radiation. The following graph shows the intensity of the different wavelengths radiated by black bodies at 6000 K compared with bodies at 255 K, along with the absorption spectrum of carbon dioxide. Use the graph to explain your answer.



Question 15 (2 MARKS)

Explain how and why the spectrum of radiation emitted by the Earth is different from the spectrum entering the atmosphere.

Question 16 (3 MARKS)

Any planet with an atmosphere will experience a greenhouse effect. Venus is no exception. Venus' atmosphere is 96.5% carbon dioxide and is closer to the Sun, so it receives more solar radiation.

Use your understanding of the greenhouse effect and the information provided to determine whether Venus would be warmer or cooler than Earth. Explain your answer.

Previous lessons

Question 17 (2 MARKS)

A beaker of water loses 17 kJ of energy to its surroundings while having 9.0 kJ of work done on it. Calculate the change in internal energy of the beaker. Give your answer in kJ.

Question 18 (6 MARKS)

The surface of a building emits a peak wavelength of 9760 nm.

a Find the building's external temperature. Provide your answer in degrees Celsius. Take Wien's constant b to be 2.898×10^{-3} m K. (3 MARKS)

b Find the change in power radiated into the environment if the building's external temperature is doubled, considering the initial radiative power is 5356 W. (3 MARKS)

Key science skills

Question 19 (3 MARKS)

Endrico and Bronte are having a discussion about the scientific meaning of the word 'theory' with reference to the greenhouse effect. Endrico tries to convince Bronte that a theory is the same as a hypothesis. Bronte claims that, in science, the term theory is only used when something has been repeatedly confirmed by experimental evidence.

Evaluate each of their claims.

3E MODELLING EFFECTS ON THE CLIMATE

We have now explored how energy flows throughout the Earth, Earth's energy budget, and the greenhouse effect. Now we are going to look at how changes to conditions on Earth affect these phenomena. What happens when Earth retains more or less energy, and how does this relate to modern climate change?

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot points

- analyse changes in the thermal energy of the surface of Earth and of Earth's atmosphere
- analyse the evidence for the influence of human activity in creating an enhanced greenhouse effect, including affecting surface materials and the balance of gases in the atmosphere
- explain how concepts of reliability, validity and uncertainty relate to the collection, interpretation and communication of data related to thermodynamics and climate science

Key knowledge units

What affects the climate?	1.1.17.1
Do humans affect the climate?	1.1.18.1
How is climate data collected, interpreted, and communicated?	1.1.20.1

No previous or new formulas for this lesson

Definitions for this lesson

albedo a measure of how much solar radiation is reflected by the Earth or by a particular surface

climate the long-term (minimum 30 years) average weather of a planet or region

enhanced greenhouse effect the magnification of the greenhouse effect due to increased greenhouse gas levels that are a result of human activity

feedback where a change is amplified (positive feedback) or suppressed (negative feedback) due to the effects of that change

weather the state of the atmosphere at a particular time

What affects the climate? 1.1.17.1

OVERVIEW

Physical changes to the Earth can affect how much thermal energy it retains. Many of these changes induce feedback, enhancing or inhibiting the change.

THEORY DETAILS

Weather refers to the state of the atmosphere (such as its temperature or rainfall) on a particular day or at a particular time. The climate of a region can be thought of as its average pattern of weather. Climate change refers to changes in the conditions of the Earth, such as temperature or precipitation (rainfall), that last for a long period of time. In general, for a change to be considered by scientists as climatic, it needs to persist for a period of more than 30 years. For example, our global average temperature having increased by more than 1°C since the industrial revolution is an example of a climatic change.

As we covered in Lesson 3D, the Earth's energy budget is a balance between the rate that energy is received by the Earth and the rate that it leaves the atmosphere. For our purposes, we can ignore the relatively small variations in the rate that energy is received from the Sun and emitted from the Earth's surface.

The factors that are much more variable are:

- How much of the radiation emitted from Earth is absorbed by greenhouse gases and re-emitted back down to the Earth.
- How much of the radiation received from the Sun is reflected (not absorbed) by the Earth, known as albedo.

If these factors are changed in some way, we will see a change to the Earth's energy budget and the amount of energy it retains, affecting Earth's temperatures.

Greenhouse gases

A change in greenhouse gas levels in the atmosphere will alter the amount of Earth's radiation that is re-emitted back down to Earth. For example, let's consider what would happen if we planted a large number of trees.

Trees absorb and store carbon dioxide (CO_2). So if a large number of trees grow, the amount of carbon dioxide in the atmosphere will decrease. As CO_2 is a greenhouse gas, we expect less radiation emitted by Earth will be absorbed by the atmosphere. As such, there will be a decrease in the amount of energy that the Earth retains, decreasing global temperatures.

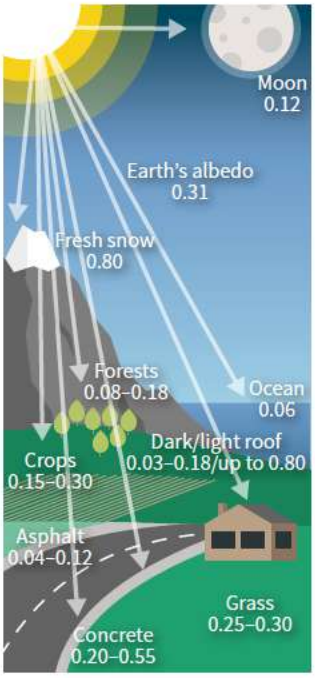


Figure 1 The albedo of various surfaces

Albedo

Albedo is a measure of how much incoming solar radiation is reflected by a surface. It takes a value between 0 and 1, like emissivity (as covered in Lesson 3B). A surface on Earth with an albedo of 0.1 would reflect 10% of incoming solar radiation. A white surface has a high albedo, as it reflects a large percentage of incoming solar radiation. In contrast, dark surfaces tend to have a low albedo. Clouds and the Earth's surface largely determine Earth's albedo.

Sea ice has a high albedo of 0.5–0.7 (0.9 with snow on top), which is much higher than that of the ocean. As such, a decrease in the amount of ice and snow covering the globe will result in a decrease in the amount of solar radiation reflected, and hence an increase in the amount of energy that the Earth retains.

Table 1 Some factors that can affect the albedo of the Earth's surface

Change in sea ice coverage (positive feedback)
Land clearing
Urbanisation

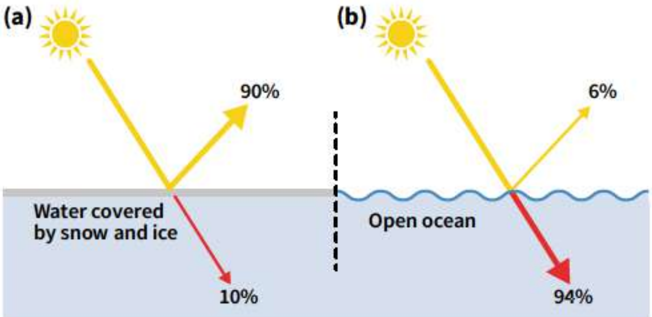


Figure 2 **(a)** The albedo of snow- and ice-covered water compared with **(b)** the albedo of open ocean. Sea ice is generally covered by snow for most of the year.

Positive feedback

Positive feedback refers to a scenario where a change is magnified due to the effects of that change. Microphones continuously picking up sound emitted by nearby connected speakers (resulting in a hideous, high-pitched sound) is a common example of positive feedback.

If there are higher temperatures one year, the Earth's average sea ice coverage will likely be reduced. This would result in a greater amount of energy being absorbed by the Earth and cause a higher temperature. In turn, this would result in more ice melting and even less sea ice coverage! This is an example of **positive feedback**.

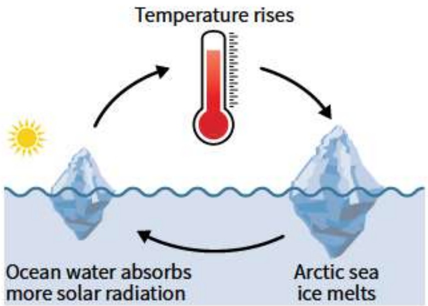


Image: KPP/Shutterstock.com

Figure 3 Melting of sea ice and temperature positive feedback loop

Negative feedback

Another type of feedback is negative feedback. It refers to scenarios where a change is suppressed due to the effects of that change. One example of negative feedback arises when there is, for whatever reason, an increase in the number of plants on Earth. The greater number of plants reduce CO_2 levels (as plants store CO_2), which leads to a reduction in the growth of new plants (as plants breathe CO_2). The initial increase in plants is eventually reduced by its effects, so this process is negative feedback. In this case, there is still an increase in the number of plants, but importantly the increase is less than it would have been otherwise (i.e. if CO_2 levels did not affect plants).

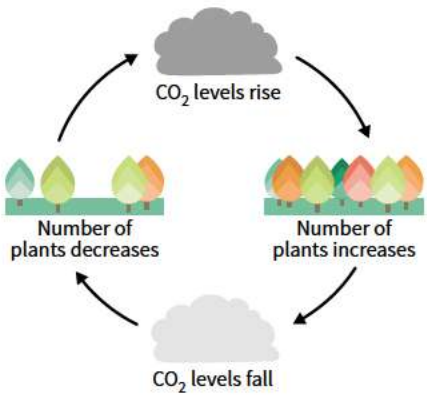


Figure 4 Number of plants and CO_2 negative feedback loop

Table 2 Other examples of climate feedback

Evaporation (positive feedback) • Higher temperatures result in more evaporation of water. • Since water vapour is a greenhouse gas, this increases the temperature further.
Ocean temperature (positive feedback) • When their temperatures rise, oceans store less CO_2, so CO_2 is released into the atmosphere. • Since CO_2 is a greenhouse gas, this increases the temperature further.
Change in sea level (negative feedback) • Higher sea level means more CO_2 is absorbed by oceans. • Since CO_2 is a greenhouse gas, this decreases the temperature. – Less sea ice melts so the sea level rises less. – The water contracts so the sea level rises less.

Do humans affect the climate? 1.1.18.1

OVERVIEW

Humans change the climate by altering the concentration of greenhouse gases in the Earth's atmosphere, and by changing the albedo of the Earth's surface. The increase in greenhouse gas concentration since the industrial revolution due to human activity is known as the enhanced greenhouse effect.

THEORY DETAILS

The burning of carbon-based fuels, known as fossil fuels, releases carbon dioxide. Since the industrial revolution, a large amount of these fuels has been burned by humans. Because of this, atmospheric CO_2 levels have increased at a drastic rate (compared to the natural rate that CO_2 levels have changed in the past). It takes hundreds to thousands of years before CO_2 naturally leaves the atmosphere, meaning that CO_2 emissions have a significant long-term effect on the climate.

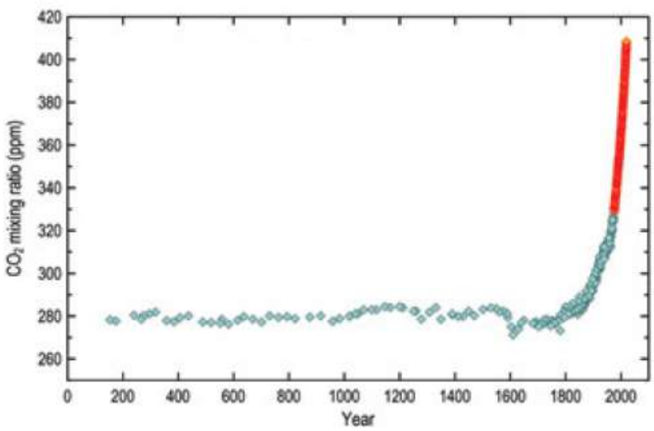


Image: © Copyright CSIRO Australia, 18 January 2019

Figure 5 Carbon dioxide concentrations over the last 2000 years, as of 2019. Note the graph's vertical axis starts at 250 ppm. The blue points come from analysing samples of Antarctic ice from deep below the surface (ice cores), while the red points come from sampling the air. The unit ppm stands for 'parts per million'.

Table 3 Examples of fossil fuels

Coal
Oil
Petrol
Natural gas

This drastic rise in CO_2 levels is a hot topic of modern climate theory, and is the primary driver behind what is known as the enhanced greenhouse effect, which is the magnification of the greenhouse effect due to human activity. The result of this is that global temperatures are currently rising.

The rate temperature is rising is:

- boosted by an overall positive feedback between greenhouse gas levels and temperature.
- significantly higher than historical rates of warming in the past hundreds of thousands of years (around ten times higher).
- believed by scientists to pose a significant danger to most of Earth's species, including humans.

It is important to remember that global temperatures are determined by the total amount of energy retained by the Earth – this is why the enhanced greenhouse effect has such a significant impact despite the fact it leads to only a relatively small increase in the amount of Earth's radiation absorbed by the atmosphere.

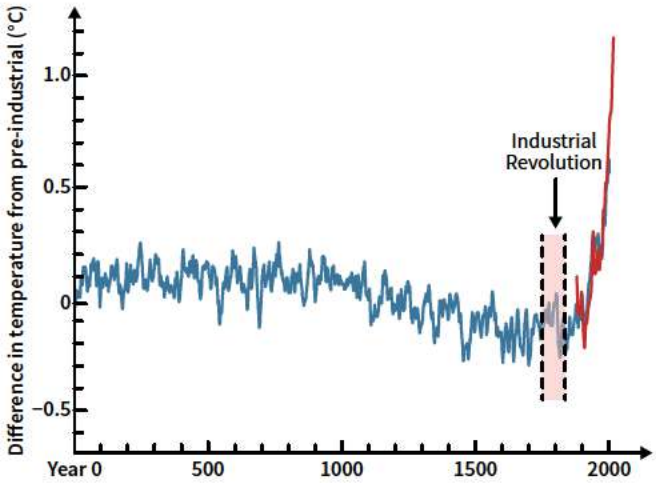


Figure 6 Global temperatures in the last 2000 years, up until 2019. The blue line shows data from indirect measurements (of ice cores, tree rings and coral), while the red line is from direct measurements starting from 1880.

CRITICAL KNOWLEDGE

There is an overwhelming consensus amongst climate scientists that humans are causing the Earth to warm – primarily due to the enhanced greenhouse effect.

Other greenhouse gases are emitted by humans too. For example, livestock produce great amounts of methane. Compared to CO_2:

- Methane is significantly better at absorbing Earth's radiation.
- Methane has a much shorter lifetime in the atmosphere (decades)
  - This means CO_2 builds up for much longer than methane.

Because CO_2 has a longer lifetime and is emitted at much higher rates, CO_2 contributes more to the greenhouse effect over the long term.

Humans do not just affect the Earth's energy budget by emitting greenhouse gases. For example, humans also change the albedo of the landscape through urbanisation and deforestation.

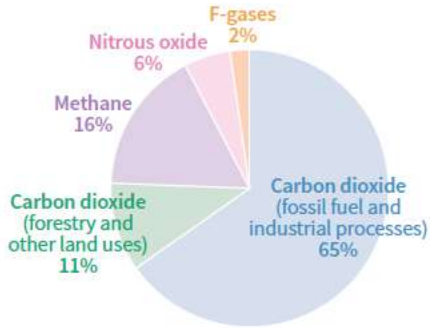


Figure 7 Proportion of global greenhouse gas emissions by gas

How is climate data collected, interpreted, and communicated? 1.1.20.1

OVERVIEW

Like in all areas of science, climate science relies on experiments and data collection in order to make predictions about the world. Due to the necessity for nations to use such predictions to inform their policies, it is not only important that scientists produce predictions that have as high reliability and validity as possible, but also that they can detail the uncertainty in their predictions.

THEORY DETAILS

The Intergovernmental Panel on Climate Change (IPCC) is an international organisation widely considered to be the leading authority on climate change. It involves thousands of scientists, and its goal is to provide assessment on the impact of climate change, as well as provide and assess the effectiveness of possible responses to mitigate or cope with climate change.

The goal for the IPCC is to provide policymakers with assessments that can guide them in determining effective responses. In Lesson 1C we covered the concepts of validity, reliability, and uncertainty. Let's consider how these concepts relate to the methods of climate scientists.

Validity

In order to produce valid results, climate scientists need to measure what was intended to be measured. If scientists were aiming to collect data to help determine whether atmospheric CO_2 levels are increasing, it would be considered invalid if they collected air samples right outside a coal power plant as they would not be representative of average atmospheric air.

An example of a good place to collect air samples for data on atmospheric air would instead be the Mauna Loa observatory. Located on the volcano of Mauna Loa in Hawaii, the observatory is far away from urban areas, vegetation, and the continents, and it is at a height where abnormal, localised effects are mostly mitigated. Any data that is affected by volcanic emissions, local traffic, or local vegetation is excluded. This reduces any contamination of results.

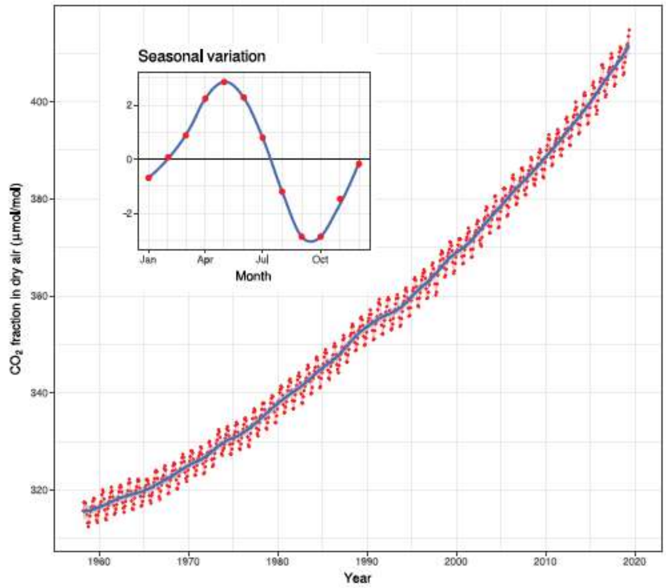


Figure 8 Atmospheric CO_2 concentrations as measured by the Mauna Loa observatory, forming what is known as the 'Keeling Curve'. The red dots are the average measured concentration of CO_2 each month, forming a cyclic pattern due to seasonal variation in CO_2 stored by plants. Note the vertical axis does not start at 0.

Reliability

For data to be reliable (and valid), it must be both repeatable and reproducible. Scientists collect data multiple times in order to ensure that their results are consistent and thus correct (repeatability). In addition, results implied by the data can only be considered correct if they agree with data collected by other climate scientists (reproducibility).

Figure 9 The Mauna Loa observatory.

The Mauna Loa Observatory constantly collects data, and its instruments are constantly recalibrated. Since they obtain consistent results, their sampling can be considered repeatable.

The Keeling Curve (seen in Figure 8) has been independently reproduced at many other locations, confirming the trend. Figure 10 highlights the importance of reproducing results – while the data looks different in many respects (due to differences in location, experimental equipment, and techniques), each experiment's data follows the same long-term trend. Although we cannot interpret, for example, the maximum average global carbon dioxide level in a given year, we can conclude with high confidence that CO_2 levels have been rising at a rate that has increased over time.

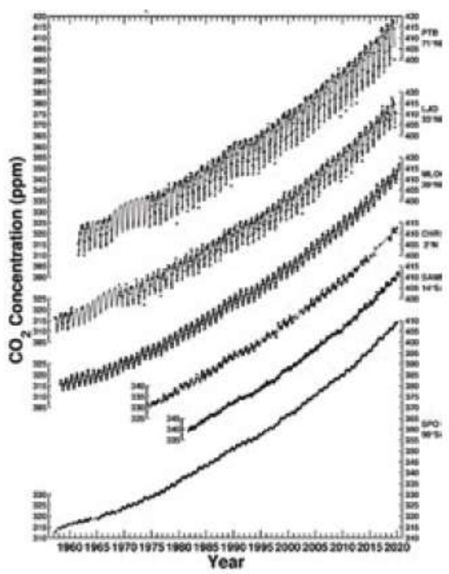


Figure 10 CO_2 levels measured by different global stations (the Mauna Loa Observatory's results are third from the top). The dots are the average monthly CO_2 concentration.

Uncertainty

Even though scientists attempt to minimise it, uncertainty is inevitable in scientific studies. It is extremely important for scientists to make the uncertainty of data clear when presenting it. This also applies to predictions made from that data. Confidence intervals are used to indicate the range of likely true values for a measurement. By using confidence intervals, scientists can convey the likelihood of the climate evolving within a certain range. Confidence intervals are used for both real data and predictions (see Figure 11).

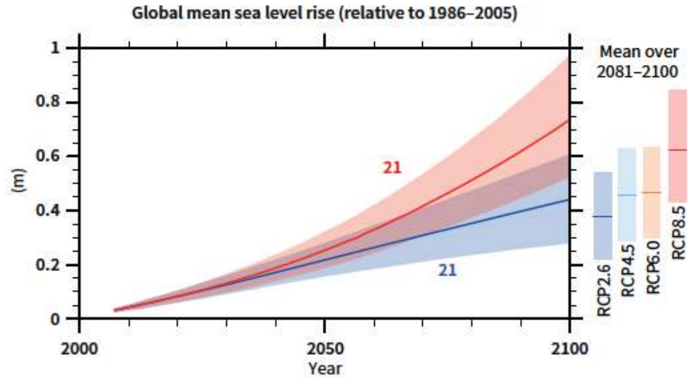


Figure 11 Predictions for the amount that sea levels will rise based on different assumptions about human CO_2 emissions. The shading in this graph represents the confidence interval.

To supplement quantitative measures of uncertainty (which are based on models), when giving predictions about the future, the IPCC will state the likelihood of certain outcomes, and the confidence they have in these predictions (based on evidence and consensus).

Good scientific practice

Good scientific practice means presenting data in a clear way that is not misleading. Some examples of practices which can be misleading, and should be avoided or highlighted for readers, are:

- Deliberately leaving out context to data by "cutting off" axes in graphs
  - Cutting off axes (truncation) is not always bad practice; it is often useful to highlight interesting results. But if it hides an overall trend, or makes a normal change look abnormal, then it can be misleading.
- Using logarithmic axes in graphs
  - Again this can be a useful tool, but only if it is clear for the reader.
- Selectively excluding valid data
  - Excluding data with low validity is appropriate.
- Implying that one variable affects another just because there is a correlation between them – correlation does not imply causation
  - Rising temperatures are held by climate scientists to be primarily driven by greenhouse gas emissions not just because of the correlation between CO_2 and temperature, but also scientific theory, computer simulations, and a lack of counterevidence despite the enormous amount of research done.

Scientists review each others' work to ensure its quality in a process known as peer review. Work that has passed peer review is considered by experts in the field to have high validity. Journals and scientific organisations, such as the IPCC, have mandatory peer review processes that help guarantee the validity of their journal.

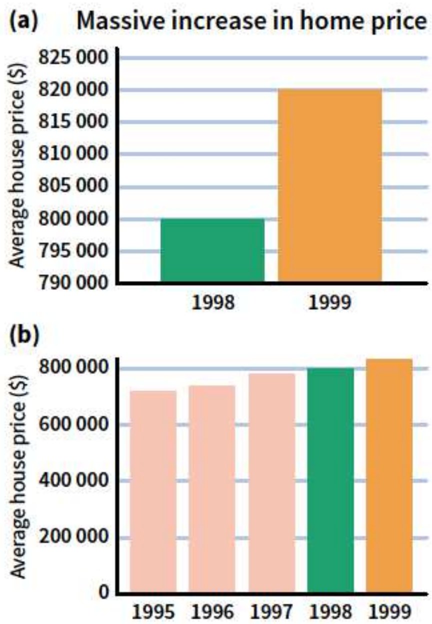


Figure 12 Bar charts representing house prices of a region. **(a)** Combined with this graph's title, this graph could mislead some viewers to believe that housing prices have more than doubled when **(b)** the full graph shows there is actually only a slight increase.

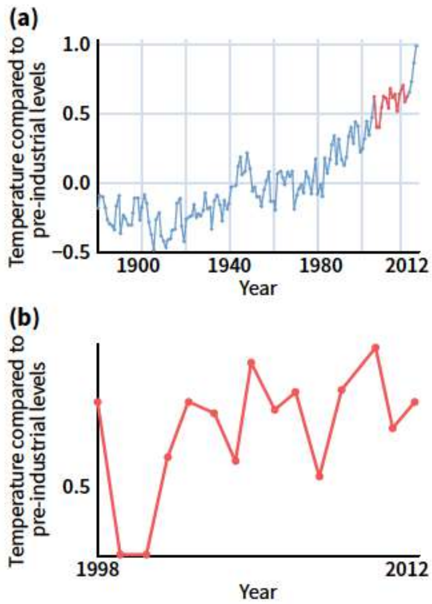


Figure 13 **(a)** The portion of the plot highlighted in red ends at about the same temperature it started; **(b)** selectively displaying this data could be used to incorrectly imply a pause (or end) in the Earth's warming (note its time period is less than 30 years).

Theory summary

- The climate of a region can be thought of as its weather's long-term average.
- Earth's energy budget is affected by physical changes to the Earth, such as changes to its albedo, carbon cycle, and oceans.
- A process causing a physical change to the Earth can have positive or negative **climate change feedback**.
  - Positive feedback is where the effects of a change result in the change being amplified.
  - Negative feedback is where the effects of a change result in the change being suppressed.
- Humans cause physical changes to the Earth, affecting the atmosphere's greenhouse gas levels and the ground's albedo.
  - Significantly more CO_2 is in the atmosphere due to human emissions, resulting in what is known as the **enhanced greenhouse effect**.
- The average global temperature is rising at a rate much faster than expected for natural climate change
- Climate scientists spend a great deal of effort attempting to determine the validity, reliability, and uncertainty of the data they collect and the predictions made with that data, in order to communicate predictions and advice that is both informative and transparent.

KEEN TO INVESTIGATE?

Climate Action Tracker – Australia
climateactiontracker.org/countries/australia

NASA article: The Carbon Cycle
earthobservatory.nasa.gov/features/CarbonCycle

NASA article: Milankovitch (Orbital) Cycles and their role in Earth's Climate
climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate

Website: Skeptical Science
skepticalscience.com/about.shtml

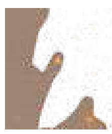
YouTube video: Kurzgesagt – In a Nutshell – Who Is Responsible for Climate Change?
youtu.be/ipVxxxqwBQw

CONCEPT DISCUSSION QUESTION

A change in the Earth's climate is generally required to last for more than 30 years to be considered true climate change. Discuss why this specific time period might have been chosen.

Answers on page 504

Hints
What is the climate a measure of?
Why is it important that the time period is not much shorter?
Why is it important that the time period is not much longer?



3E Questions

THEORY REVIEW QUESTIONS

Question 1

Suppose that in the year 3000, the Earth has been cooling down over the previous century. However, new research reveals that it has been heating quite rapidly over the past decade. Could we conclude that, in the year 3000, the Earth's climate is one that is warming?

A Yes

B No

Question 2

For **a**-**c**, select the option that is an example of a changing climate.

a **A** The polar ice caps shrinking over many thousands of years.

B An abnormally high loss of ice from the ice caps in a single day.

b **A** A week of particularly hot weather.

B A significantly greater number of hot days in the last 50 years compared to the 50 years before that.

c **A** A hurricane hitting a coastal town.

B A steady decrease in the frequency of hurricane formation over many centuries.

Question 3

If a surface on Earth has an albedo of 0.8 then it is good at

A absorbing and emitting light out to space.

B absorbing and emitting solar radiation out to space.

C reflecting light.

D reflecting solar radiation.

Question 4

Which of the following are examples of negative feedback? *(Select all that apply)*

I When global temperatures decrease, the ice coverage of the Earth increases, causing temperatures to decrease.

II When global temperatures decrease, CO_2 levels decrease, which causes global temperatures to decrease further.

III When global temperatures increase, CO_2 levels increase, which causes global temperatures to increase further.

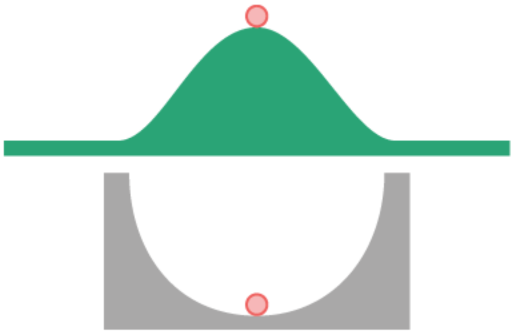
IV When the temperature of the Earth decreases, less black body radiation is emitted, so the Earth cools less.

Question 5

Consider scenario A, where a ball is on the top of a hill. And scenario B, where a ball is at the bottom of a half-pipe.

A

B



We now give the ball a small initial speed to the right in each scenario.

In which scenario would we immediately observe positive feedback in the ball's speed?

Question 6

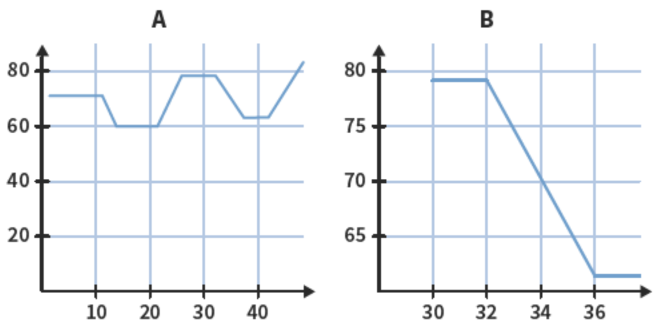
Which of the following affects the rate the temperature of the Earth changes?

A The imbalance between the amount of greenhouse gases entering and leaving the atmosphere.

B The amount of greenhouse gases in the atmosphere.

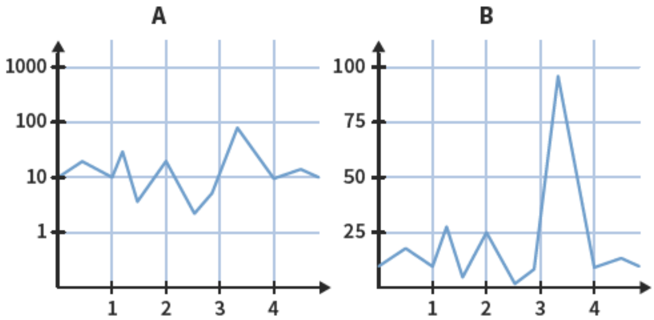
Question 7

Which of the following graphs (derived from the same data) might be considered misleading?



Question 8

Which of the following graphs (derived from the same data) might be considered misleading?



Question 9

Which of the following statements is false?

A A high uncertainty indicates a poor scientific method.

B Uncertainty can be shown in ways other than error bars.

C It is important for scientists to be transparent about uncertainty.

Question 10

Which of the following would be a more difficult prediction?

A The weather on a day a year from now.

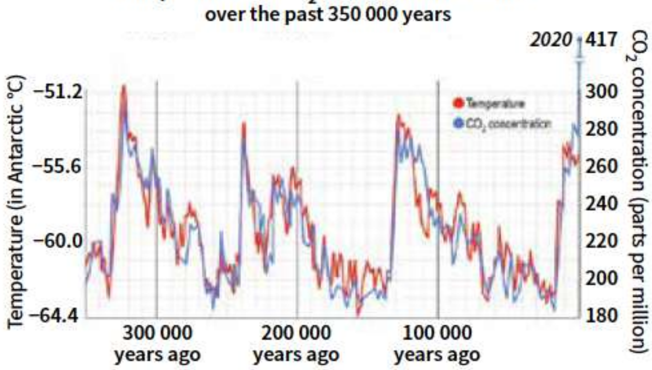
B The climate on a day a year from now.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 11 (3 MARKS)

Historically, an increase in CO_2 levels is correlated with an increase in temperature. While looking through historical data, Bec notices that often CO_2 levels do not start to increase before temperature does. She says this means that CO_2 levels are not responsible for changes in temperature.

Temperature and CO_2 from Antarctic ice cores over the past 350 000 years



Prompts

a In the greenhouse effect, a higher CO_2 concentration results in

A higher temperatures.

B lower temperatures.

C no effect.

b Given your answer for part **a**, if an increase in temperature causes CO_2 levels to increase, this change would have

A positive feedback.

B negative feedback.

C no feedback.

c Which one of the following statements is true?

A It is clear from the graph that temperature changes always occur before changes in CO_2 levels.

B It is clear from the graph that changes in CO_2 levels always occur before changes in temperature.

C There is a strong correlation between CO_2 levels and temperature, but generally it is not clear which change in quantity occurs before the other.

Question

d With reference to the provided graph and the concept of feedback, explain why Bec's claim is unjustified. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 12 (1 MARK)

The Earth's average snowfall increases one year, increasing its albedo. This will not result in

A a decrease in global temperatures.

B negative feedback.

C snowfall becoming more likely.

D changes to the weather.

Question 13 (1 MARK)

Which of the following is least likely to be helpful for understanding the climate?

A Data with unreliability

B Data with uncertainty

C Data that has had contaminated data removed

D A graph with a confidence interval

Question 14 (1 MARK)

Which of the following is the biggest driver of present climate change?

A Increasing greenhouse gas levels

B An increasing albedo

C Increasing incident solar radiation

D Decreasing radiation from the Earth's surface

Question 15 (1 MARK)

Which of the following would not contribute to the enhanced greenhouse effect?

A A coal-fired power plant emitting CO_2

B Cars burning petrol

C A volcano spewing greenhouse gases into the atmosphere

D An arsonist setting a tree on fire

Question 16 (1 MARK)

The total increase in retained energy due to the enhanced greenhouse effect is insignificant compared to the total amount of energy flowing in and out of the Earth. Why, then, does the enhanced greenhouse effect cause an abnormal increase in global temperatures?

A An increase in temperature is dependent on the amount of energy retained, not the total amount of incoming energy.

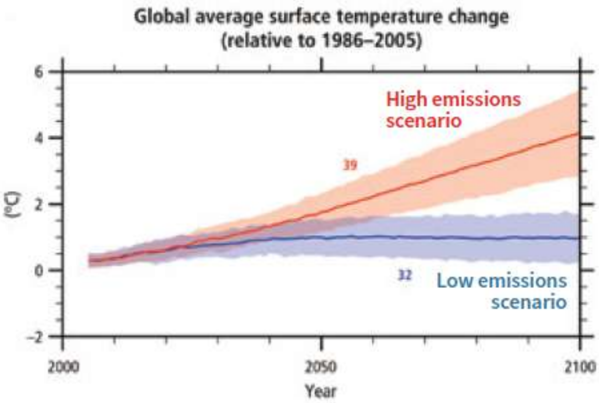
B Only humans can cause an increase in global temperatures.

C Both of the above

D Scientists still cannot explain this.

Question 17 (1 MARK)

The following diagram displays historical and predicted global average surface temperature change, under two scenarios.



Assuming a high emissions scenario, which of the following has the highest likelihood of being true?

A The global average surface temperature will be a little over 4.0 degrees warmer in the year 2100.

B The global average surface temperature will be somewhere between 3.0–5.5 degrees warmer in the year 2100.

C The global average surface temperature will be somewhere between 0.25–1.8 degrees warmer in the year 2100.

D The temperature of a day a year from now will be somewhere between 2.0–6.0 degrees warmer than the temperature today.

Question 18 (2 MARKS)

Explain why carbon dioxide's contribution to the enhanced greenhouse effect becomes more significant compared to methane over longer time scales.

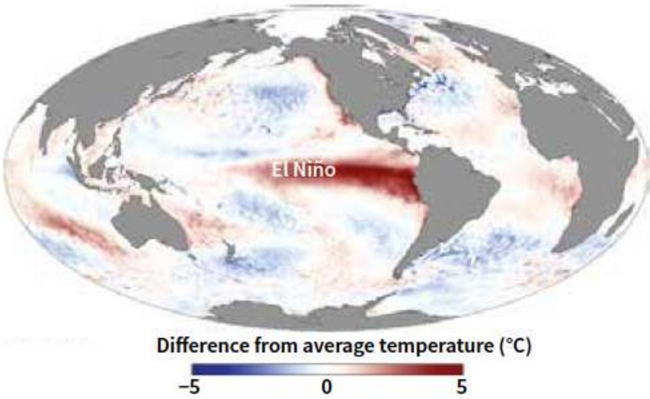
Previous lessons

Question 19 (1 MARK)

State the Zeroth Law of Thermodynamics.

Question 20 (3 MARKS)

El Niño events are periods in which the average temperature of areas of the Pacific Ocean can rise 3–5 degrees as seen in the provided figure. This warming extends to the western coast of South America, making the ocean warmer than the land for longer periods of time – what effect would you expect this to have on the onshore/offshore winds on South America's western coast? Justify your answer.



Key science skills

Question 21 (2 MARKS)

Explain how climate scientists ensure reliability when collecting and interpreting data.

3F THERMODYNAMIC PRINCIPLES IN HOUSING AND TRANSPORTATION

How can the design of a house have an impact on the environment and on power bills? VCE Physics students are required to apply thermodynamic principles to investigate one or more issues related to the environment with reference to the enhanced greenhouse effect. This lesson provides an introduction to just some of the concepts that students might investigate. Students should use the list of online resources that appear in the 'Keen To Investigate?' box at the end of the lesson, along with any other resources available, to investigate an issue in greater depth.

3A The electromagnetic spectrum	3B Thermal radiation	3C Earth's energy flow	3D The greenhouse effect	3E Modelling effects on the climate	3F Thermodynamic principles in housing and transportation

Study design dot point

- apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity with reference to the enhanced greenhouse effect:
  - proportion of national energy use due to heating and cooling of homes
  - comparison of the operation and efficiencies of domestic heating and cooling systems: heat pumps; resistive heaters; reverse-cycle air conditioners; evaporative coolers; solar hot water systems; and/or electrical resistive hot water systems
  - possibility of homes being built that do not require any active heating or cooling at all
  - use of thermal imaging and infrared thermography in locating heating losses in buildings and/or system malfunctions; cost savings implications
  - determination of the energy ratings of home appliances and fittings: insulation; double glazing; window size; light bulbs; and/or electrical gadgets, appliances or machines
  - cooking alternatives: appliance options (microwave, convection, induction); fuel options (gas, electricity, solar, fossil fuel)
  - automobile efficiencies: fuel options (diesel petrol, LPG and electric); air delivery options (naturally aspirated, supercharged and turbocharged); and fuel delivery options (common rail, direct injection and fuel injection)

Key knowledge units

Why heating and cooling designs matter	1.1.19.1
Passive designs	1.1.19.2
Active heating and cooling systems	1.1.19.3
Automobile efficiencies	1.1.19.4
Example questions for investigation	1.1.19.5

No previous or new formulas for this lesson

Definitions for this lesson

fossil fuel a material that started as living organisms and has transformed into an energy-dense fuel as a result of geological processes over millions of years. Examples include coal, oil, and gas

non-renewable energy source an energy source that is not replaced or that is replaced at a slower rate than it is being used

particulates small, distinct solids such as dust or soot that are suspended in a liquid or gas

renewable energy source an energy source that is constantly replaced at a greater rate than it is being used

volatile the property of changing between the liquid state and the gaseous state easily

Why heating and cooling designs matter 1.1.19.1

OVERVIEW

Heating and cooling accounts for the majority of energy used by Australian households. This means it is particularly important to design heating and cooling systems that are efficient and to reduce the reliance of these systems on non-renewable energy sources.

THEORY DETAILS

Around 90% of the energy produced for use in Australian households comes from the non-renewable fossil fuels coal and gas. Non-renewable fuels will eventually run out if we continue to use them. Of the **total energy** used by an average Australian household:

- 40% of the energy is used to heat and cool the house.
- 21% of the energy is used to heat water.
- Over 10% of the energy is used for cooking and refrigeration.

This means that **over 70% of the energy used in Australian households is used for heating and cooling** people, places, and things. The remaining 25–30% is used to run other appliances.

We should care about this large amount of energy use and, in particular, the amount of that energy that is generated from non-renewable fossil fuels for three reasons.

- Costs: On average, energy bills cost between $500 and $1500 per person each year (depending on the number of people living in the household).
- Energy sustainability: We will eventually run out of the fossil fuels that currently provide most of this energy.
- Environment: The burning of fossil fuels, which produces much of the energy we use, releases greenhouse gases which lead to the enhanced greenhouse effect (discussed in Lesson 3E).

In general, there are two ways that we can reduce the amount of energy that we consume from non-renewable fossil fuels (without having to sacrifice the comforts of modern living) and, hence, address the issues of cost, sustainability, and the environment.

- Firstly, we can increase the amount of energy that is **produced** from renewable sources, such as solar and wind, and decrease the amount that is produced from fossil fuels as shown in Figure 1. This can reduce costs because renewable energy continues to become cheaper as technology improves while non-renewable energy becomes more expensive as its negative impacts are factored into its cost. Note that nuclear energy may be considered a renewable energy source although the material used in nuclear power plants is not. Nuclear energy is an important consideration for discussions about energy sources but it is not within the scope of VCE Physics.
- Secondly, we can reduce the amount of energy that is **used** both for its intended purpose and for unintended purposes (i.e. energy that is wasted) as shown in Figure 1. That is, we can try to design houses, systems, and appliances that are more energy-efficient.

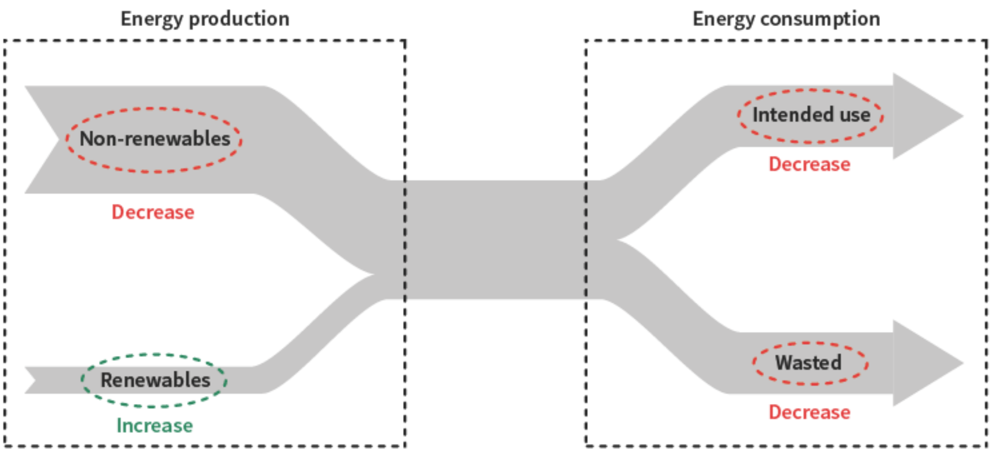


Figure 1 An energy flow diagram showing how we can change energy production and consumption to address cost, sustainability, and environmental effects

The rest of this lesson will focus on the ways that we can reduce energy consumption in household heating and cooling and in transportation.

Passive designs 1.1.19.2

OVERVIEW

Passive designs take advantage of the natural climate to regulate the temperature without the need for fuel or active electrical systems and appliances.

THEORY DETAILS

A good passive design can minimise a household's heating and cooling energy consumption. Passive designs aim to either encourage or prevent the movement of thermal energy from natural sources, such as sunlight and cool breezes, to keep a house cool in summer and warm in winter. In this section, we will discuss six considerations for good passive design.

Orientation, shading, and passive solar heating

Direct sunlight can provide about the same amount of heat to each square metre as a bar radiator. Clever passive designs allow as much sunlight into the house as possible during winter and minimise exposure to sunlight in summer.

Orientation describes the direction of important features in a building, such as its windows, relative to the seasonal variations in the position of the Sun. Since Australia is in the southern hemisphere, the Sun traces an arc across the northern part of our sky between when it rises in the east and sets in the west.

- In summer, the Sun traces an arc that is higher in the sky (at a greater angle above the horizon).
- In winter, the Sun traces an arc that is lower in the sky so its position is closer to the northern horizon than in summer. See Figure 2.

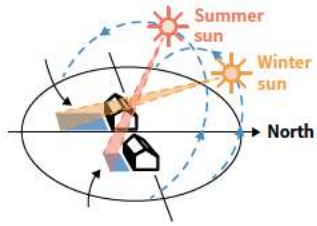


Figure 2 The Sun's arcs across the sky in Australia during summer and winter

Designing a house so that its width has large windows facing north, as shown in Figure 3, maximises passive solar heating during winter. An overhanging part of the roof called an eave can effectively shade the window from direct sunlight during summer when the Sun is higher in the sky.

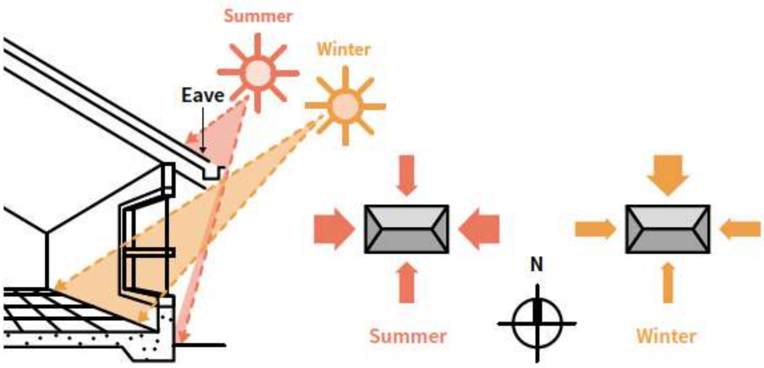


Figure 3 A north-facing window allows a lot of sunlight into the house during winter but not as much direct sunlight in summer if an eave is used.

Deciduous trees – which drop their leaves during autumn and grow new leaves during spring – that are planted on the north side of a house also help to create shade during summer and allow sunlight to reach the house during winter. An awning (extended part of a building to create shade over a window) can do a similar job to an eave. Constructing the awning from louvres (a set of slats) that are set at an angle parallel to the sunlight in winter, can very effectively allow sunlight in winter while reflecting it in summer. These methods are shown in Figure 4.

An alternative to an eave or awning is to keep window blinds closed during summer to minimise the incoming radiation.

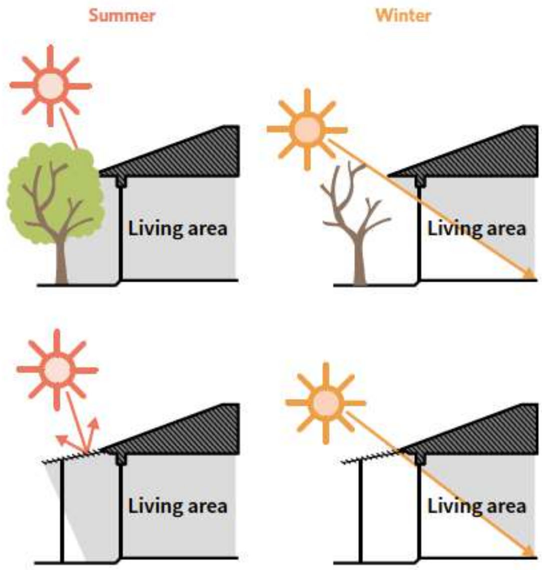


Image: radoma/Shutterstock.com

Figure 4 Deciduous trees and awnings made from louvres are particularly effective at creating shade in summer and allowing the sunlight to enter in winter.

Passive cooling

The movement of air is particularly important for cooling houses because it can carry warm air out and replace it with cooler air. It also encourages evaporative cooling (which was covered in Lesson 2C).

One simple way of encouraging air movement through a house is to use well-placed openable windows to allow air to flow through the house in the direction of prevailing wind patterns in that location.

The Sun's energy can also be used to move air in the form of convection currents when there are openings at different heights and sides of the house with a path for the air to flow between the openings. This is particularly effective for houses with multiple storeys. This design relies on the principle that warm air rises. This warm air can escape from a higher opening, which draws cool air from a lower opening through the house, as shown in Figure 5.

Figure 6 shows a solar chimney, which takes advantage of the same principle. It absorbs radiation from the Sun and heats up the air inside the chimney, which then rises. This creates air movement through the house as it draws air from the house into the bottom of the chimney. A rotating turbine may be used to assist the natural convection. It can also be used to push the warm air back down the chimney and into the house in winter.

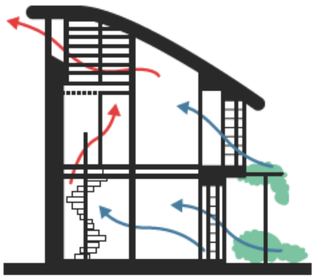


Figure 5 Natural convection creating air movement to cool a house

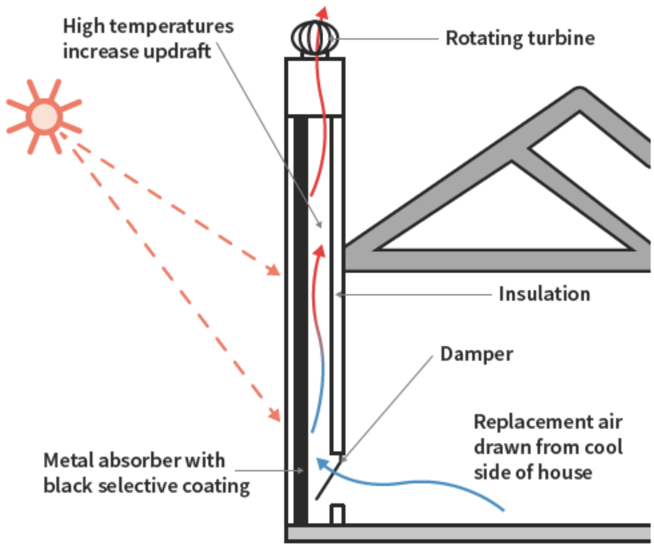


Figure 6 A solar chimney

When there is water near a house, evaporative cooling can be encouraged by designing the house so that the incoming air (due to natural breezes or convective air movement) passes over the water. This can reduce the temperature of the air entering the house by several degrees.

Sealing

Gaps in a house allow air to leak. This can reduce the effectiveness of heaters and air conditioners by allowing unwanted heat loss in winter and unwanted heat gain in summer. Some of the most common gaps through which leakage occurs in houses are shown in Figure 7. Air leakage can be responsible for up to 25% of heat loss in winter so sealing these gaps is one of the simplest and most effective ways to reduce a household's energy consumption.

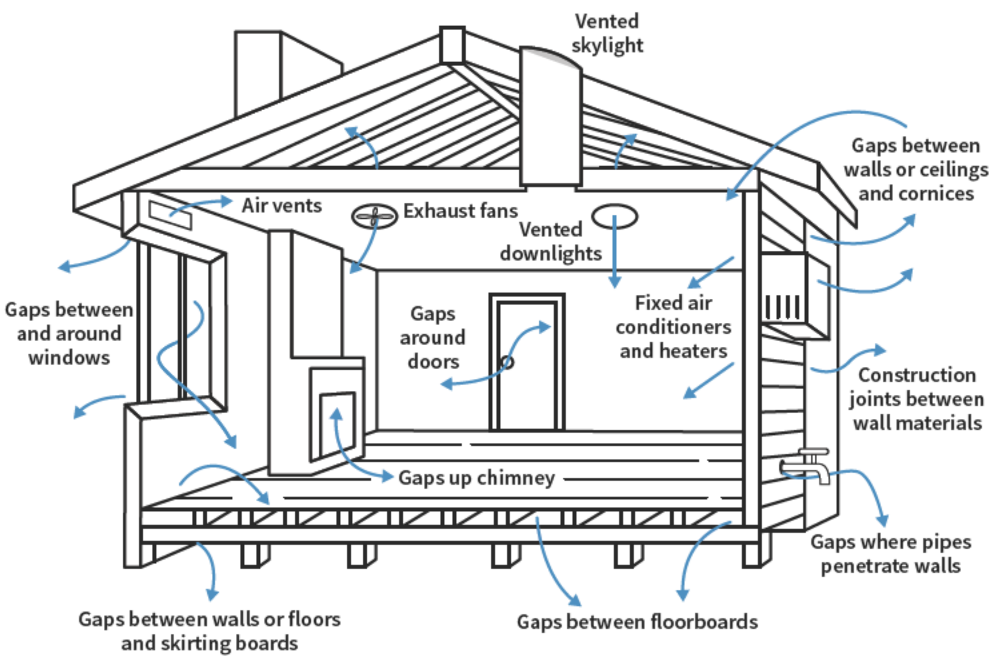


Figure 7 Common air leakage points

Insulation

Insulation is material that is installed in roofs, between walls, and in floors to reduce heat loss in winter and heat gain in summer. It reduces conduction due to the material's insulating properties as the name suggests. It can also reduce convection by preventing air flow around the walls and the roof. Insulation also commonly uses a reflective foil to reduce absorption and emission of radiation.

Image: SpeedKingz/Shutterstock.com

Figure 8 A builder installing insulation in a roof. The material is a poor conductor and it has a reflective surface to reduce radiation.

Glazing

While windows are an important feature of a house to allow natural light, ventilation, and a view, they also account for up to 40% of a house's heating energy being lost during winter and up to 87% of its heat gained during summer.

The section titled 'Orientation, shading, and passive solar heating' discussed ways that heat transfer via **radiation** (sunlight) can be managed to help heat a home in winter but not in summer. Additionally, there are many types of glass that reflect, transmit, absorb, and emit radiation to various extents so that a house can be designed with the optimal type of window for its environment.

However, these methods do not help prevent heat loss and gain via **conduction**. Double and triple glazed windows, shown in Figure 9, reduce conduction. They consist of two (or three) panes of glass with air or some other inert gas trapped between them. The thermal insulating properties of the air or gas helps to reduce conduction through the windows by around 50%. Closed blinds can be used for a similar purpose as the second pane of glass – to provide a physical barrier between the air in the house and the glass – but they are less effective than double glazed windows. In addition, selecting an insulating material for the window frames can have a significant effect.

Image: Bacho/Shutterstock.com

Figure 9 Sections of triple and double glazed windows

The need for better-designed windows, insulation, or sealing can be identified using infrared thermography, which will show places where heat is leaking in or out of a house, as shown in Figure 10.

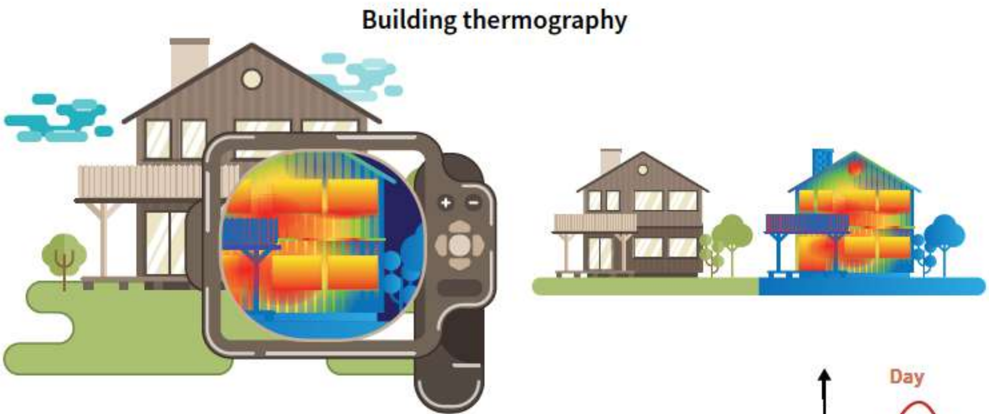


Image: VectorMine/Shutterstock.com

Figure 10 Infrared thermography depicting the windows as red, which means they are allowing heat to escape rapidly.

Thermal mass

Thermal mass describes the property of absorbing, storing, and re-releasing thermal energy. It is a direct application of the heat capacity of a material (covered in Lesson 2C). In the context of building construction, large concrete slabs and bricks are examples of materials that are considered to have a high thermal mass. A thermal mass absorbs heat during the day and releases that heat during the night to moderate the temperature fluctuations in the house. The graph in Figure 11 shows the relative fluctuations in household temperature for various thermal masses as the outside temperature changes between daytime and nighttime.

Thermal mass can help keep a house warmer at night in winter and cooler during the day in summer (see Figure 12). However, thermal mass should be combined with other passive design features to avoid making the house too cold during winter or too hot during the night in summer.

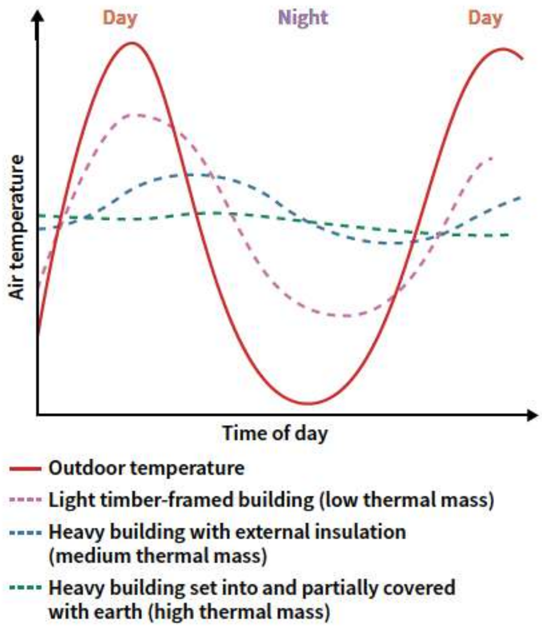


Figure 11 Temperature fluctuations between day and night for houses with different thermal masses

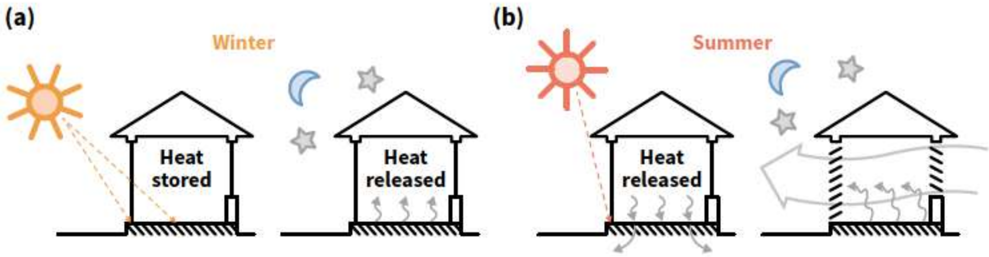


Figure 12 **(a)** Effective use of thermal mass in winter can store heat during the day to be able to warm the house during the night. **(b)** In summer, it can remove heat from the house during the day and then expel the heat outside during the night.

Active heating and cooling systems 1.1.19.3

OVERVIEW

Active heating and cooling systems are commonly used to complement passive designs or to do the majority of the job of keeping a house comfortable that has not incorporated good passive designs. However, these systems are often expensive and contribute to the enhanced greenhouse effect.

THEORY DETAILS

High efficiency heating and cooling systems, along with behavioural change and perhaps small building renovations, may be a cheaper and more viable way to reduce energy costs than to rebuild or significantly renovate a home. They are also commonly used to complement passive designs. Therefore, it is important to understand which systems are efficient (and under what conditions) and which systems are inefficient.

Most active systems rely either on gas as a fuel source or electricity. In Victoria, most of the electricity we use is generated from the burning of coal. Table 1 compares the amount of carbon dioxide produced per unit of energy obtained when these fuel sources, and others which will be discussed in relation to transportation, are burned.

Table 1 Comparison of the amount of carbon dioxide released per unit of energy for different fuel sources

Fuel	Mass of CO_2 released per gigajoule produced
Coal	Around 90 kg (depending on coal type)
Diesel fuel and heating oil	70 kg
Petrol	65 kg
Propane	60 kg
Natural gas	50 kg

Heat pumps

Heat pumps move (or 'pump') thermal energy via a volatile substance known as a refrigerant from colder regions to warmer regions. This means that the hot region gets hotter and the cold region gets colder. It is also known as a reverse cycle air conditioner.

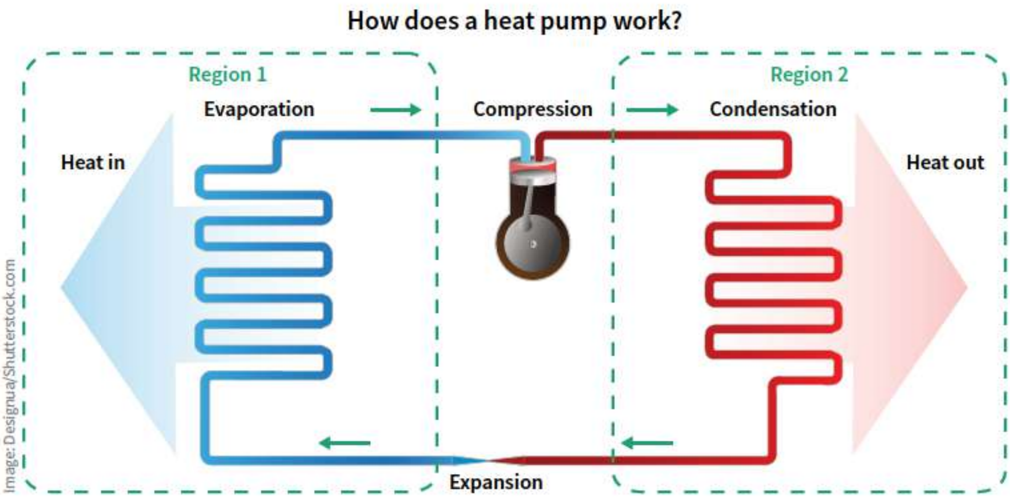


Figure 13 The operation of a heat pump. Thermal energy is moved from Region 1 to Region 2. Refrigerant flows around the circuit in the direction shown by the green arrows.

Figure 13 represents the basic operation of a heat pump, which is as follows:

- A gaseous refrigerant flows from Region 1 to a compressor. The compressor does work on the refrigerant by squeezing it, which raises its temperature **above that of Region 2**.
- The refrigerant flows to a coil in Region 2 where heat transfers by conduction from the refrigerant to the surrounding air. This heats up Region 2 and the refrigerant cools down enough to condense into a liquid.
- The liquid refrigerant flows out of Region 2 to an expansion valve, which reduces the pressure of the refrigerant so that it turns into a gas. Work is done by the refrigerant as it expands so it cools down to a temperature **below that of Region 1**.
- The gaseous refrigerant flows to a coil in Region 1 where heat transfers by conduction from the surrounding air to the refrigerant. This cools down Region 1 and the refrigerant heats up.
- The gaseous refrigerant then returns to the compressor to repeat the cycle.

A reverse cycle air conditioner can reverse the direction of the flow of the refrigerant so that Region 1 and Region 2 in Figure 13 effectively swap places so that it can change between heating a house and cooling a house.

Heat pumps or reverse cycle air conditioners are a relatively efficient means of maintaining a comfortable temperature inside a house because it uses energy only to move existing thermal energy around, rather than to convert other energy forms into thermal energy.

Resistive heaters

Resistive heating is the process of passing an electric current through an element (a wire or some other electrical conductor) so that the electrical energy transforms into thermal energy and the element becomes very hot. This is the same principle that toasters use. Three examples of resistive heaters are radiant heaters, electric fan heaters, and oil column heaters.

- Radiant heaters are resistive heaters that rely on radiation to transfer thermal energy directly. There is usually reflective material behind the element to help direct the radiation forwards.
- Electric fan heaters use the same principle to heat the element, but then they use a fan to blow air past the hot element. Heat transfers from the element to the air by conduction and the warm air is then forced around the room.
- Oil column heaters also use electricity to heat an element. However, in this case heat transfers from the element to the oil inside the columns which then flow due to natural convection. This is similar to the way that water is heated up in a kettle. The hot columns of oil then warm the surrounding air by conduction and emit some radiation into the room.

Image: Maxx-Studio/Shutterstock.com

Figure 14 A radiant heater

Resistive heaters are often cheap to buy and they can be useful for heating small spaces but they generally use a lot of energy which makes them expensive to run. Most of the electricity that supplies these devices in Victoria is derived from coal which produces a lot of greenhouse gases per joule.

Gas is a cleaner-burning fuel than coal and gas heaters transform the chemical energy of the gas directly into thermal energy (without converting to or from electrical energy, which can be inefficient). For these reasons, gas heaters generally have a much lower impact on the environment.

Evaporative coolers

Lesson 2C covered the way that evaporation draws heat from the surroundings and, therefore, cools them down. Evaporative coolers rely on this principle. They pump water from a reservoir to a cooling pad, and then use a fan to blow hot air through the pad. The water in the pad takes heat from the air as it evaporates, so the outgoing air is cooler. Evaporative air conditioning is an energy-efficient method of cooling a house because it needs only to pump water and blow air. However, evaporative cooling does not work effectively in humid conditions, which can be a significant issue on hot days in many parts of Australia.

Solar hot water systems

The Sun provides a tremendous amount of energy – around 18 MJ per square metre per day. Given that about one-fifth of the energy used by a household is used to heat water, a simple and efficient way of harnessing the Sun's energy is to allow water to absorb solar radiation to heat up. This avoids the inefficiencies associated with converting energy to and from electrical energy.

Solar hot water systems consist of a series of tubes or pipes that are good at absorbing solar radiation through which the water circulates. The tubes are usually installed on the roof of a house where they receive the most sunlight. The most efficient way of running a solar hot water system is to use the process of natural convection to circulate the water between a storage tank and the tubes. However, depending on the amount of hot water needed and the rate that the water heats up, an electric pump might be used to circulate the water. Even when an electric pump is used, solar systems are very efficient ways of providing hot water.

Image: Hill120/Shutterstock.com

Figure 15 A solar glass tube hot water panel

Electrical resistive hot water systems

Electrical resistive hot water systems operate in a very similar way to a kettle. Electricity is used to heat an element at the bottom of an insulated tank of water. The element heats the surrounding water by conduction. The thermal energy is then distributed throughout the tank through natural convection. Due to water's high specific heat capacity, this uses a lot of electricity. As a result, this type of hot water system is expensive and it indirectly creates a lot of greenhouse emissions per joule due to the coal that is burnt to produce the electricity.

If solar hot water is not an option, then a gas-heated water system is better for the same reasons that gas heaters are better than resistive heaters.

Automobile efficiencies 1.1.19.4

OVERVIEW

Transportation accounts for about one quarter of Australia's total energy consumption. Most countries in the world use a similarly large amount of energy for transportation. Therefore, transitioning to vehicles that are more efficient and less reliant on fossil fuels is an important step in reducing the enhancement of the greenhouse effect.

THEORY DETAILS

At the beginning of the 20th century, cars were powered mostly by steam and electricity (they each made up about 40% of cars) and only 20% of cars used petrol. The main reason that petrol cars dominated the vehicle market by the 21^{st} century is that Henry Ford, who happened to produce petrol-driven cars, developed the assembly line which drastically reduced the time and cost to build cars so people could afford to buy them. However, due to concerns about energy sustainability and the environment, we are now seeing a revival of other types of fuel.

Petrol

Petrol is derived from crude oil, which is a non-renewable fossil fuel. Petrol is a very energy-dense fuel, which makes it convenient since a vehicle can travel a long way with a relatively small amount of fuel. However, there are multiple downsides to petrol. Firstly, its price changes depending on oil supply which is affected by many factors out of our control (like conflicts and political changes on the other side of the world) which means it can be very expensive. In addition, as a non-renewable fuel it will run out and as a fossil-fuel it has a negative impact on our environment.

Diesel

Like petrol, diesel is derived from crude oil. Diesel is becoming an increasingly popular choice over petrol for fuelling cars because it is generally cheaper per kilometre. The reason for this is that diesel engines typically use around 20% less fuel, measured by volume, than petrol-powered vehicles per kilometre travelled. So, depending on the relative prices of unleaded petrol and diesel, a diesel car is typically cheaper to run.

However, Table 1 shows that diesel also releases more carbon dioxide per unit of energy released. Additionally, diesel produces nitrous oxide and other particulates that are harmful to human health. Therefore, diesel is not necessarily a better choice when energy sustainability and the environment are considered.

LPG

Liquefied petroleum gas (LPG) is a mixture of propane and butane that is under very high pressure so that it is stored in liquid form. It is derived from natural gas or crude oil which are non-renewable fossil fuels. The main benefits of LPG are that it produces fewer particulates than diesel, it burns more cleanly (see propane in Table 1) than diesel or petrol, and it is usually much cheaper per litre than diesel or petrol.

However it is also less energy-dense than petrol or diesel, which means LPG-powered cars need to refuel more often, and it can cause a build-up of deposits within the vehicle's fuel system which can render it less efficient.

Table 2 A comparison of the cost, carbon dioxide emissions, and particulate emissions of different car fuels on per-litre and per-kilometre bases. Comparisons are indicative only since they also depend on the efficiency of a car's engine and the costs of fuel at a particular time.

	Petrol	Diesel	LPG
Distance per volume (km/litre)	In-between	Furthest	Least
Cost per volume ($/litre)	In-between	Most expensive	Cheapest
Cost per distance ($/km)	Most expensive	In-between	Cheapest
CO_2 per volume (kg/litre)	In-between	Most	Least
CO_2 per distance (kg/km)	Most	In-between	Least
Particulates per volume or distance	In-between	Most	Least

Electric cars

An electric car uses electrical energy stored in a battery to power an electric motor. Therefore, it does not produce any greenhouse gases or other pollution at the point of use (from the car). However, it is very important to consider where the electrical energy comes from that charges the battery. In Victoria, most electricity is derived from burning coal, which releases more carbon dioxide per unit of energy than petrol, diesel, or LPG (see Table 1). However, electric cars still have many environmental and cost benefits:

- The amount of electricity that is produced from solar and wind power is steadily increasing. This means an electric car can become significantly more environmentally friendly as other renewable technologies improve (whereas a petrol car is limited to relatively small improvements).
- While petrol produces less carbon dioxide per unit of energy, combustion engines in cars are relatively inefficient. In general, more of the petrol's energy ends up wasted as heat than the coal's energy which is converted into electricity in a power plant and then converted into kinetic energy (motion) of the car. So, overall, electric cars in Victoria still create less greenhouse gas emissions per kilometre than petrol, diesel, or LPG cars.
- Electricity, even from coal but especially from renewable sources like household solar panels, is cheaper per unit of energy than from petrol.
- Electric cars have less moving parts so they do not need to be serviced very often and parts rarely need replacing.

Historically, the main drawbacks of electric cars are that they are more expensive to buy, they cannot travel as far before needing to recharge, and they cannot travel very fast. However, with more interest and investment in electric cars and better technology, these issues are being addressed. Modern electric cars are rapidly becoming competitive with – or superior to – their petrol counterparts.

Example questions for investigation 1.1.19.5

This lesson has introduced some important principles relating to heating and cooling households and the environmental impact of different automobile fuels. However, there is much more detail to explore and other applications of thermodynamic principles (such as cooking) for you to carry out an in-depth investigation. You should start with a relevant and interesting question that you can realistically try to answer. Examples of such questions include:

- How does the size of a house relate to its heating and cooling requirements? Are passive designs affected by the size of the house?
- How much energy does a typical roof receive from the Sun? How is it affected by seasonal changes or weather conditions? How is it affected by dirt?

- How much energy do various appliances around the house use? Are the energy ratings reliable?
- How do different fuel sources for cooking (such as an electric stove, an induction stove, and a gas stove) compare in terms of cost and efficiency? How do different methods of cooking (such as a conventional oven and a microwave oven) compare?
- How much energy is gained or lost due to poor insulation? How do the resulting heating and cooling costs compare with the cost of installing effective insulation?
- How do different construction materials (such as brick, timber, and concrete) compare in terms of cost and energy efficiency?
- How do different types of openable windows (such as sliding windows, louvres, and casement windows) compare? How does the size of the window affect the heat transfer through it? How much heat transfer occurs due to conduction compared with radiation?
- How much carbon dioxide is released per kilometre for a modern electric car and a modern petrol-driven car? How realistic is it that electric cars could eliminate their carbon dioxide emissions? How do fuel and air delivery systems in cars affect their efficiency?

The links provided in the Keen To Investigate box at the end of the lesson may be a helpful starting point for your investigation.

Theory summary

- The world is facing a significant challenge to reduce its reliance on fossil fuels for the sake of energy sustainability and to reduce the enhanced greenhouse effect. Energy is also expensive.
- Heating and cooling accounts for an enormous amount of Australia's energy use so it is worth focusing on ways to reduce this.
- Passive designs use natural processes to maintain a comfortable temperature in an environment. Important principles include:
  - Using the different heights of the Sun in summer and winter to minimise the amount of sunlight reaching the house in summer and maximise it in winter.
  - Using the Sun's energy for natural convection.
  - Using evaporative cooling.
  - Preventing unwanted heat transfer (both into and out of the house) using insulation, sealing gaps, and double-glazed windows for example.
- Active heating and cooling systems that **move** thermal energy (such as heat pumps or active solar hot water systems) rather than **produce** thermal energy are more efficient.
- Gas is a more efficient fuel source for active heating than electric-powered heating systems.
- Fuel sources for cars are diversifying with various pros and cons for both cost and the environment. Electric cars have the greatest potential since they depend on the source of the electricity.

KEEN TO INVESTIGATE?

ABC 'Problem diesel filters "widespread"'
abc.net.au/news/2019-11-08/diesel-filter-problems-in-australian-cars-widespread/11655040

Australian Government 'Energy information and services'
energy.gov.au

Australian Government 'Green Vehicle Guide'
greenvehicleguide.gov.au

Australian Government 'Your Home'
yourhome.gov.au

CSIRO 'Australian Housing Data'
ahd.csiro.au

EIA 'How much carbon dioxide is produced when different fuels are burned?'
eia.gov/tools/faqs/faq.php?id=73&t=11

Lawrence Livermore National Laboratory 'Estimated International Energy Flows 2007'
flowcharts.llnl.gov/content/international/2007EnergyInternational.pdf

Tesla
tesla.com/en_au

The Concord Consortium Energy 2D simulation
energy.concord.org/energy2d/

Victorian Government 'Heating options for your home'
sustainability.vic.gov.au/You-and-your-home/Save-energy/Heating/Choose-energy-efficient-heating

Window Energy Rating Scheme
wers.net

CONCEPT DISCUSSION QUESTION

A refrigerator is an application of a heat pump. Discuss whether a refrigerator with its door left open would cool down the room it is in.

Answers on page 505

Hints

What happens to the thermal energy that is removed from the cool side of a heat pump?

Overall, does a heat pump decrease the amount of thermal energy in a system?

3F Questions

THEORY REVIEW QUESTIONS

Question 1

Approximately what percentage of an average Australian household's energy use is used for heating and cooling (including heating water, cooking, and refrigeration)?

A 10%
B 25%
C 40%
D 70%

Question 2

For the purpose of good passive design, which side of a house in a cold climate in the **northern hemisphere** should have large windows?

A North
B South
C East
D West

Question 3

Good passive designs for heating and cooling

A maximise heat gain.
B minimise heat gain.
C maximise heat loss.
D minimise heat loss.
E All of the above depending on the season

Question 4

Which of the following features of a house can **both** reduce heat loss and reduce heat gain? *(Select all that apply)*

I Insulation
II Eaves
III Double glazed windows
IV Sealing gaps
V Solar chimneys

Question 5

Household insulation can reduce heat transfer due to

A conduction.
B convection.
C radiation.
D All of the above

Question 6

What is the best description of the purpose of thermal mass in passive design?

A To keep a house warm in winter
B To keep a house cool in summer
C To reduce variation in household temperature between day and night

Question 7

Why are heat pumps a relatively efficient way of heating or cooling a space?

A They do not rely on electricity or a fuel source to create thermal energy.
B They do not rely on electricity or a fuel source.

Question 8

Georgia lives in tropical Queensland, which has a high humidity, and Greg lives in Alice Springs, which generally has a low humidity. For which person would an evaporative air conditioner be more effective?

A Georgia

B Greg

Question 9

When comparing the polluting impact of different automobile fuel sources, it is best to compare

A the amount of pollution per litre of fuel.

B the amount of pollution per dollar.

C the amount of pollution per kilometre.

Question 10

When comparing the cost of different automobile fuel sources, it is best to compare

A the cost per litre of fuel.

B the cost per unit of carbon dioxide released.

C the cost per kilometre.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 11 (3 MARKS)

Michelle is designing a new home. She plans to use shade as a way of reducing heat gain. She would also like to use the sunlight to cool the home.

Prompts

a What happens to air that is warmer than the surrounding air?

- **A** It sinks below the surrounding air.
- **B** It rises above the surrounding air.
- **C** It immediately reaches thermal equilibrium by sharing its thermal energy with the surrounding air.
- **D** Unless there is some other force, nothing happens.

b How can this effect be used to cool a house?

- **A** The still air feels cooler than moving air.
- **B** The house cools down as the warm air transfers heat to the surrounding air.
- **C** Air movement has a cooling effect and the moving warm air can draw in cooler air from outside to replace it.
- **D** The air cools down due to its movement.

Question

c How can the Sun's energy be used (not just blocked) to cool a house? (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 12 (2 MARKS)

Insulation is very important to keep a house warm in cold environments. Does that mean that insulation should not be used in hot environments? Explain your answer.

Question 13 (1 MARK)

Identify the main type of heat transfer that double glazing reduces.

Question 14 (2 MARKS)

Provide two reasons why gas is preferred to electricity for active heating systems in Victoria.

Question 15 (3 MARKS)

Todd notices that electric cars do not have an exhaust pipe and concludes that driving an electric car must not create any greenhouse emissions. Explain why this statement is not necessarily true and describe the reasons that electric cars are still a helpful way of reducing greenhouse emissions (now and in the future).

Previous lessons

Question 16 (1 MARK)

In which region of the electromagnetic spectrum do objects at room temperature radiate most energy?

Question 17 (2 MARKS)

Why do greenhouse gases prevent a greater proportion of energy from leaving the Earth's atmosphere than the proportion of energy that they prevent from entering the Earth's atmosphere?

Key science skills

Question 18 (3 MARKS)

A student is investigating the rate of heat loss through various types of windows during winter using a thermal imaging camera. He measures the heat loss through windows at ten different houses between mid afternoon and evening. Comment on the validity of this investigation.
Justify your response.

CHAPTER 3 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

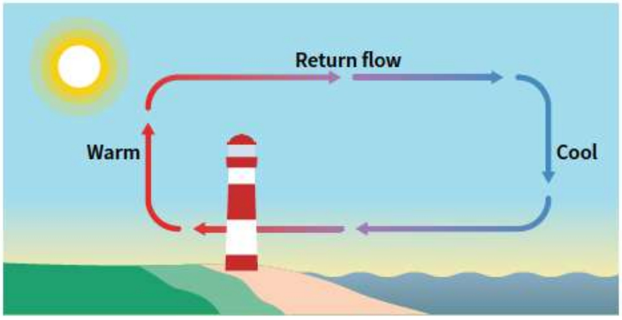
SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Air movements are often a result of convection cells.
Identify the convection cell shown in the diagram.



A Offshore wind

B Onshore wind

C Hadley cell

D Trade wind

Question 2

Which of the following is not a greenhouse gas?

A Carbon dioxide

B Methane

C Water vapour

D LPG (liquefied petroleum gas)

Question 3

A deciduous tree is outside a north-facing window of a family home in Australia. If it were removed, what type of heat transfer would increase the home's temperature in summer?

A Conduction

B Convection

C Radiation

D Convection currents

Question 4

The enhanced greenhouse effect is different to the greenhouse effect as it is

A reducing the amount of carbon dioxide in the atmosphere causing the atmosphere to warm.

B driven by humans.

C increasing the amount of carbon dioxide in the atmosphere causing the atmosphere to cool.

D a result of natural changes to the planet's atmosphere.

Question 5

If a distant star has a peak wavelength of 230 nm, what is its temperature? Take Wien's constant b to be 2.898×10^{-3} m K.

A 12 600 K **B** 10 000 K **C** 5700 K **D** 126 K

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

Identify two properties common to all electromagnetic waves.

Question 7 (3 MARKS)

Describe the process of convection in the Earth's solid mantle, being sure to explain how the conditions in the mantle allow this to occur.

Question 8 (8 MARKS)

A light for a photography studio and a flashlight both send current through a high-resistance filament so that it reaches a high enough temperature to emit light. The radiation emitted by the studio light is a pure white colour, but the flashlight has a yellowish tinge.

a Which light is at a higher temperature? Justify your answer. (3 MARKS)

Before the flashlight is turned on it has a temperature of 20.0°C, but the label states that the operating temperature of the filament is 3500 K with an operating power output of 30 W.

b Calculate the power output of the flashlight before it is turned on. (3 MARKS)

c Calculate the peak wavelength of the light after it has reached operating temperature. Take Wien's constant, *b*, to be 2.898×10^{-3} m K and give your answer in nanometres. (2 MARKS)

Question 9 (4 MARKS)

Explain how greenhouse gases in the atmosphere contribute to the greenhouse effect. Use a diagram to help explain your answer.

Question 10 (5 MARKS)

The provided table shows the CO_2 released per kilometre and the annual fuel cost of three comparable vehicles. Currently, the electric vehicle is being powered by electricity mainly produced through the burning of fossil fuels.

Vehicle	CO_2 released due to electricity/fuel (g/km)	Annual fuel cost ($AUD)
Electric vehicle	169	789
Petrol vehicle	173	1625
Diesel vehicle	148	1061

a If choosing a vehicle just by its current amount of CO_2 released, which vehicle is the best choice? (1 MARK)

b If choosing a vehicle just by its annual fuel cost, which vehicle is the best choice? (1 MARK)

c Explain why electric vehicles have a CO_2 release associated with their operation, and hence which vehicle would be the best choice, based on the amount of CO_2 released, if electric vehicles were powered by renewable electricity. (3 MARKS)

Question 11 (3 MARKS)

Explain positive feedback with reference to a real-world example.

UNIT 1, AOS 1 REVIEW

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

The average temperature of the Moon increased for several years after the Apollo landings. It is suspected that astronauts disturbed the lunar soil – resulting in darker lunar soil covering the Moon's surface. This could have caused an increase in temperature by

A decreasing the Moon's albedo.

B increasing the Moon's albedo.

C reducing the Moon's greenhouse effect.

D enhancing the Moon's greenhouse effect.

Question 2

Which one of the following is closest to the work done by a system that has an increase in internal energy of 10 kJ while 5 kJ of heat is transferred to it? Assume no work is done on the system.

A −15 kJ **B** −5 kJ **C** 5 kJ **D** 15 kJ

Question 3

Which one of the following regions of the electromagnetic spectrum is emitted by the Sun with the least intensity?

A Infrared **B** Visible **C** X-rays **D** Ultraviolet

Question 4

A thermometer is brought to the temperature of a cake, and then to the temperature of its cake tin. The thermometer measures that the cake is slightly hotter than its tin.

Which one of the following best describes how thermal energy is flowing in this scenario? Ignore convection and radiation.

A Thermal energy is flowing from the cake to the tin, and will continue to do so until the cake is colder than the tin.

B Thermal energy is flowing from the cake to the tin, and will continue to do so until they reach thermal equilibrium.

C Thermal energy is flowing from the tin to the cake, and will continue to do so until the cake is colder than the tin.

D Thermal energy is flowing from the tin to the cake, and will continue to do so until they reach thermal equilibrium.

Question 5

An ice cube in a freezer at a temperature of −6°C is losing thermal energy via conduction at a rate of 2 J s^{-1}. The rest of the inside of the freezer is at a temperature of −18°C. Ignore convection and radiation. When the ice cube's temperature is −12°C, the rate it will be losing heat due to conduction is closest to

A 1 J s^{-1}.

B 2 J s^{-1}.

C 4 J s^{-1}.

D 12 J s^{-1}.

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (3 MARKS)

A chemist is trying to create a liquid that is good at transferring energy through conduction, convection, and radiation. She can modify the liquid's reflectivity, thermal insulation, and viscosity (how easily the liquid flows). Which heat transfers will each of these three properties affect?

Question 7 (2 MARKS)

The provided diagram shows a hot electric heater (above room temperature) sitting in an otherwise empty, air-filled room. On a copy of the provided diagram, sketch a convection cell that could be generated by the heater.

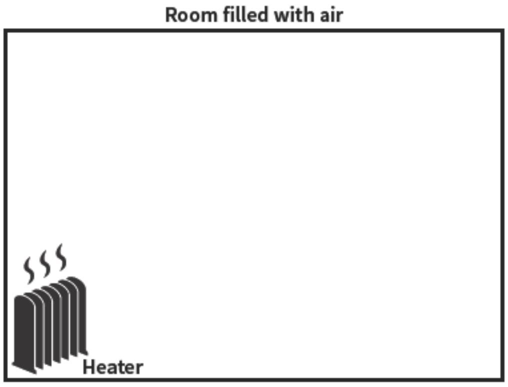


Image: A-spring/Shutterstock.com

Question 8 (3 MARKS)

System *A* has more of its internal energy stored as potential energy than kinetic energy. System *B* has a higher temperature than system *A*. The two systems are placed in thermal contact.

a Will the internal energy of system *B* increase or decrease? (1 MARK)

b Will the change in system *A*'s potential energy and kinetic energy be equal? Briefly justify your answer. (2 MARKS)

Question 9 (4 MARKS)

The uneven distribution of the Sun's radiation drives large-scale convection cells in the Earth's atmosphere. However, not all light warms the atmosphere.

a Which of the interactions with light (absorption, transmission, reflection) directly warms the atmosphere? (1 MARK)

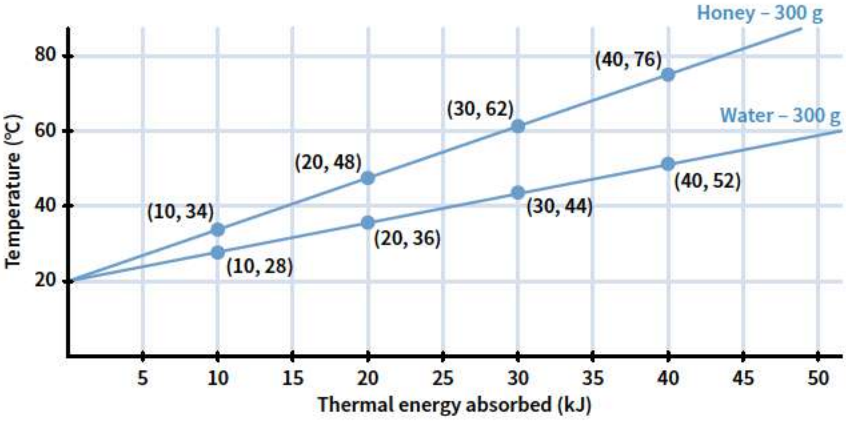
b Because radiation warms the Earth, sometimes the atmosphere is warmed up through an interaction with the Earth's surface.

Detail this interaction and where on Earth (relative to the equator) this warming of the atmosphere is most significant. (2 MARKS)

c Name another convective process that transfers thermal energy across the Earth's surface. (1 MARK)

Question 10 (5 MARKS)

Students are investigating the specific heat capacity of honey. They heat a 300 g sample of honey and a 300 g sample of water, and plot the samples' temperature against the calculated thermal energy absorbed by the samples.



Take the specific heat capacity of water to be $c_w = 4200$ J kg^{-1} K^{-1}.

a Calculate the specific heat capacity of the honey sample. Provide your answer in J kg^{-1} K^{-1} to two significant figures. (3 MARKS)

b The students now heat a new sample of water. The sample requires the same amount of energy to increase its temperature by one degree as the 300 g honey sample.

Calculate the mass of this sample of water. (2 MARKS)

Question 11 (3 MARKS)

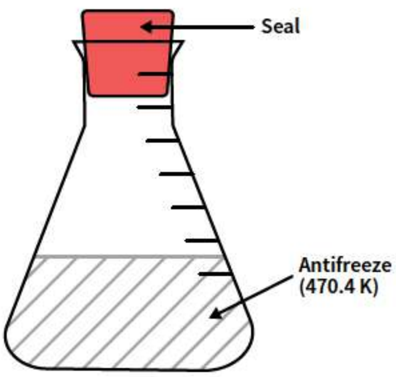
Evaporative coolers are a popular way to keep homes cool during the summer.

a Is an evaporative cooler an example of active or passive cooling? (1 MARK)

b Explain how the evaporation of water is able to cool down a thermodynamic system. (2 MARKS)

Question 12 (9 MARKS)

Colin is conducting an experiment to determine how the temperature of 150 g of an antifreeze fluid in a sealed flask changes over time. He has heated the substance to its boiling point of 470.4 K. Take the antifreeze's specific latent heat of vaporisation to be 800 kJ kg^{-1}.

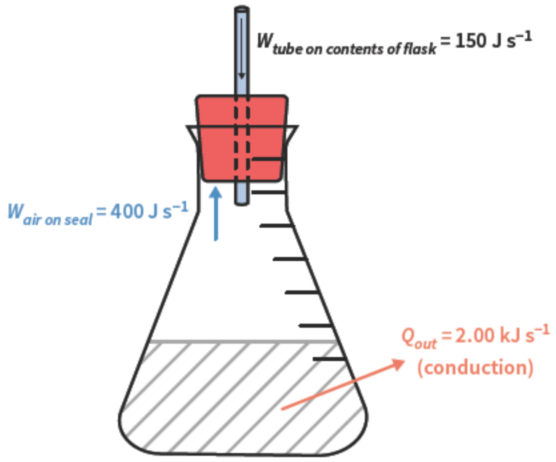


a What does temperature measure? Explain the physical meaning of 'absolute zero'. (2 MARKS)

b Determine the temperature of the antifreeze in degrees Celsius. (1 MARK)

c Calculate the minimum amount of energy the antifreeze would need to absorb to transition to a gaseous state. (1 MARK)

Due to conduction, the contents of the flask lose 2.00 kJ of thermal energy as heat every second. In addition, the hot, high-pressure air above the fluid does 400 J of work on the seal (a stopper) every second, slowly pushing it upwards. Aiming to reduce this, Colin passes a thin tube attached to an air compressor through the seal to do 150 J of work on the contents of the flask every second. The difference in temperature between the inside of the flask and its environment is currently 180 K.



d Calculate the per second change in the contents of the flask's **internal energy** when the temperature difference between the inside of the flask and its environment is 45.0 K. Assume that the rate of work being done does not change. (3 MARKS)

e If the flask was not sealed, would you predict the rate at which thermal energy leaves the antifreeze to increase, decrease, or stay the same? Justify your prediction. (2 MARKS)

Question 13 (3 MARKS)

Explain why surfaces on Earth that are good at reflecting white light have a high albedo.

Question 14 (13 MARKS)

The Australian summer of 2012–2013 was termed the "Angry Summer" due to the overwhelming number of temperature records that it broke. A study by scientists at the University of Melbourne concluded with 90% confidence that human activity had increased the likelihood of such an event by at least five times.

a What effect has the enhanced greenhouse effect had on the amount of thermal energy retained by the Earth? Explain how human activity has resulted in the enhanced greenhouse effect. (3 MARKS)

b What effect does the construction of cities with an albedo lower than the environment they replaced have on the amount of thermal energy retained by the Earth? (1 MARK)

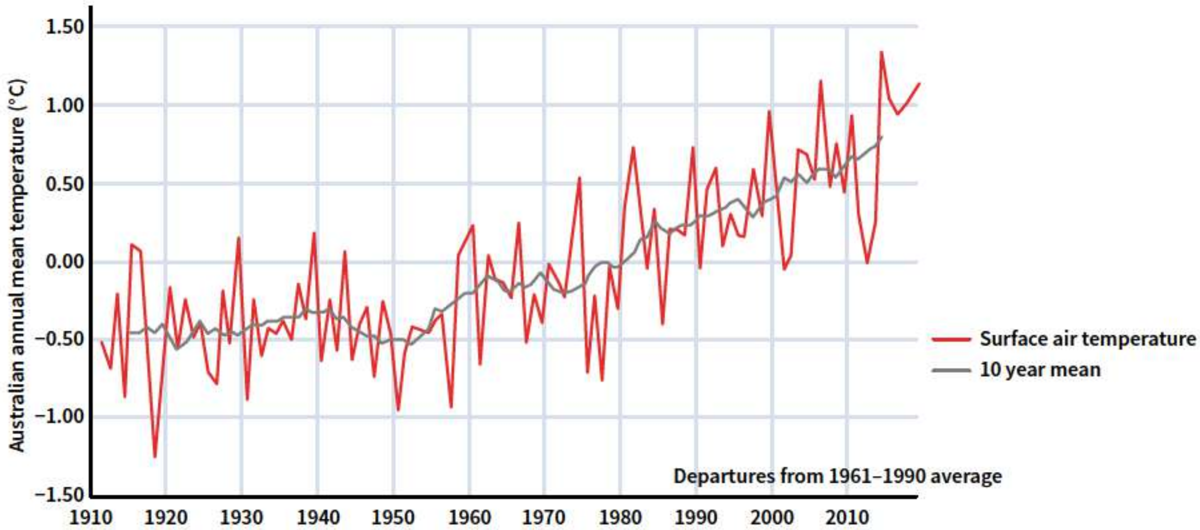
c Does the confidence level quoted in the study relate to reliability, or uncertainty? (1 MARK)

The Angry Summer achieved a record 40.3°C for the hottest average temperature on a single day in Australia. However, this record was broken on a day in 2019 when Australia experienced an average temperature of 41.9°C. Assume that Australia's temperature is the same as its average temperature.

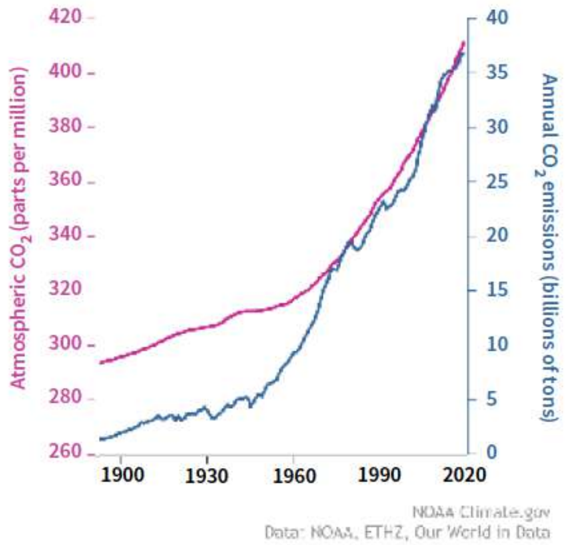
d Calculate the difference in the radiative power of Australia between these two temperatures. Take the power emitted when the temperature is 40.3°C to be 4.21×10^{15} W. (3 MARKS)

e Calculate the peak wavelength of the radiation Australia emitted when its hottest average temperature was recorded. Assume Australia is a black body. (2 MARKS)

f The first of the following graphs displays two measures of Australian temperatures, and the second displays two measures related to global CO_2 emissions.

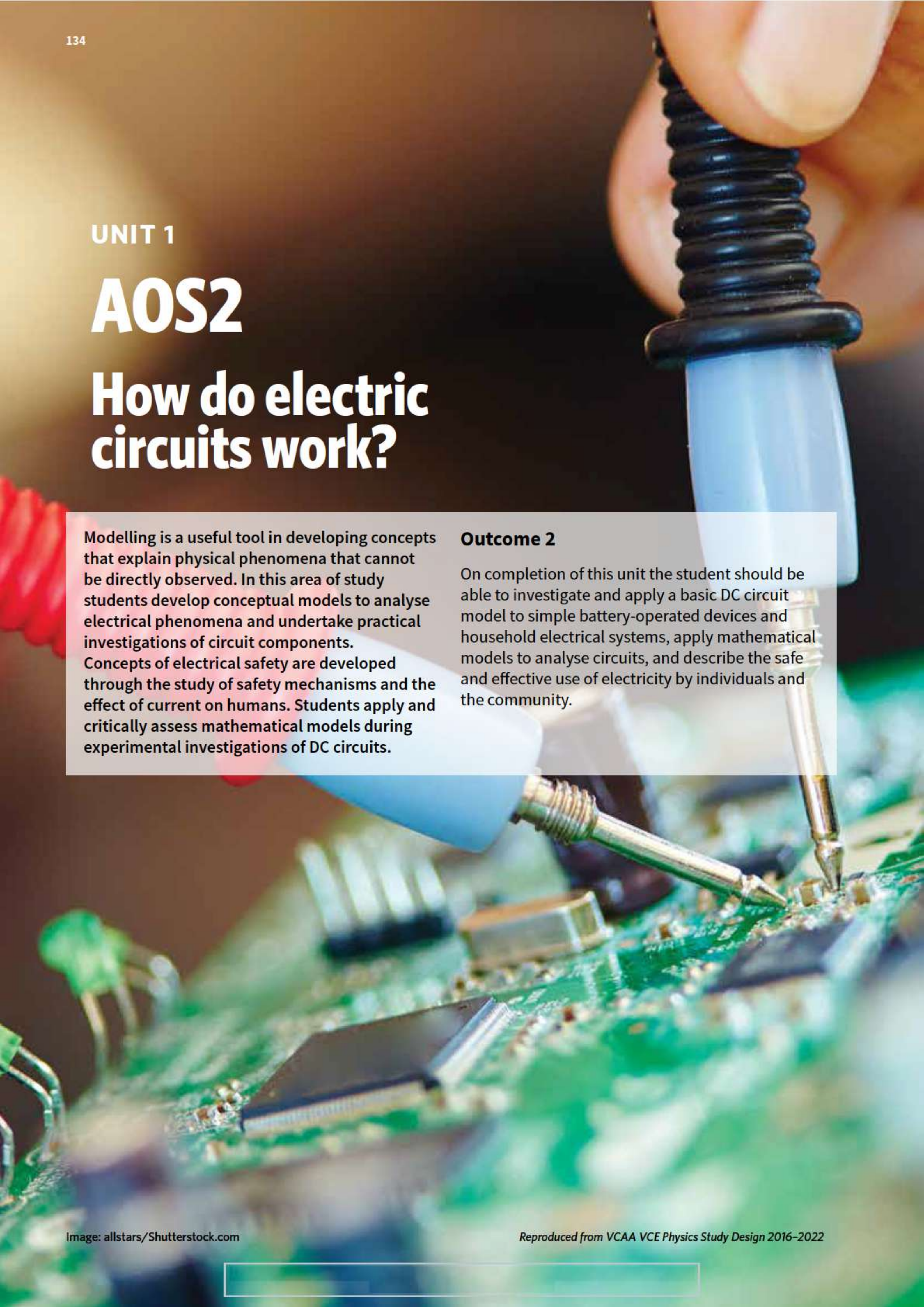


CO_2 in the atmosphere and annual CO_2 emissions (1900–2019)



After looking at the graphs, Josh concludes that they show that increases in the rate of annual CO_2 emissions are causing temperatures in Australia to increase. Therefore, humans only need to stop increasing their rate of CO_2 emissions to prevent Australia from warming further. Celia thinks that Josh cannot make this claim with the evidence provided.

Explain why Josh's claim is incorrect, and why the graphs do not justify his claim. (3 MARKS)



UNIT 1

AOS2

How do electric circuits work?

Modelling is a useful tool in developing concepts that explain physical phenomena that cannot be directly observed. In this area of study students develop conceptual models to analyse electrical phenomena and undertake practical investigations of circuit components. Concepts of electrical safety are developed through the study of safety mechanisms and the effect of current on humans. Students apply and critically assess mathematical models during experimental investigations of DC circuits.

Outcome 2

On completion of this unit the student should be able to investigate and apply a basic DC circuit model to simple battery-operated devices and household electrical systems, apply mathematical models to analyse circuits, and describe the safe and effective use of electricity by individuals and the community.

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UNIT 1 AOS 2, CHAPTER 4

Electricity and circuits

04

Key knowledge

- apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- explore different analogies used to describe electric current and potential difference
- investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$, $P = \frac{E}{t} = VI$
- justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits
- model resistance in series and parallel circuits using
  - current versus potential difference (I-V) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent effective resistance in arrangements in
    - series: $R_T = R_1 + R_2 + ... + R_n$ and
    - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$
- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers
- compare power transfers in series and parallel circuits

4A WHAT IS ELECTRICITY?

Electricity plays an important role in our day to day lives; it powers our lights, charges our phones, and even powers some of our cars. But what is electricity? Given how much we depend on electricity, it is important to explore this abstract physical phenomena even if we do not often see or feel it.

This lesson will introduce the fundamental quantities in the study of electricity: charge (Q), current (I), potential difference/voltage (V), electric energy (E), and electric power (P). Understanding these quantities and the relationships between them is essential to understanding electric circuits.

4A What is electricity?	4B Resistance and Ohm's law	4C Series circuits	4D Parallel circuits	4E Combining series and parallel circuits

Study design key knowledge dot points

- apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- explore different analogies used to describe electric current and potential difference
- investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$, $P = \frac{E}{t} = VI$
- justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits

Key knowledge units

Electric circuits	1.2.1.1
Electrical quantities	1.2.1.2 & 1.2.3.1
The hydraulic circuit analogy	1.2.2.1
Measuring electrical quantities	1.2.4.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$V = \frac{E}{Q}$ potential difference
	$I = \frac{Q}{t}$ electric current
	$P = \frac{E}{t}$ power
	$P = VI$ electric power

Definitions for this lesson

charge a fundamental property of subatomic particles responsible for electric interaction

charge carrier a charged particle that contributes to an electric current

conventional current the direction of flow of positive charge

current (electric) the rate of movement of charge with respect to time requiring the movement of charged particles

direct current (DC) electric current that flows in a constant direction

electric potential energy potential energy due to the separation of charge

potential difference the amount of electric potential energy per unit charge between two points

power the rate of change of energy with respect to time

voltage see potential difference

Electric circuits 1.2.1.1

OVERVIEW

Electric circuits are closed loops that allow electricity to flow. Circuits and their components help us to use electricity in many different ways.

THEORY DETAILS

An electric circuit is a loop of connected electrical components. If there is a break in the connection, current will not flow in the loop, even when a potential difference is applied. A common way to break a circuit is to use a switch, which allows the circuit to be closed or opened at will.

Circuit diagrams

In circuit diagrams, electrical components are represented by unique symbols, and the lines that join them represent electric wires. Figure 1(a) shows the real circuit and circuit diagram for a cell (DC voltage source) and light bulb connected by wire. In Figure 1(b), a switch has been added to the circuit so the light can be turned on and off.

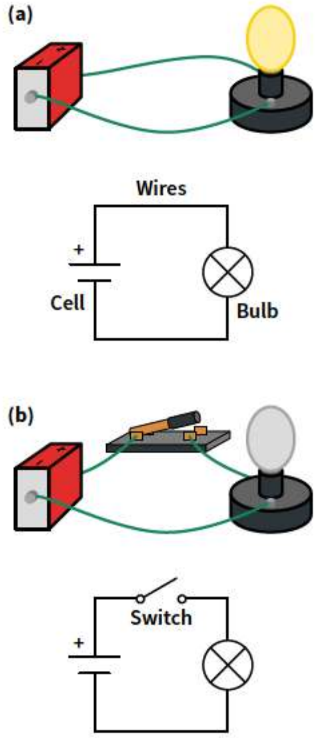
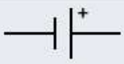
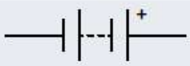
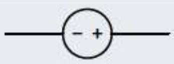
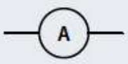


Figure 1 **(a)** The real circuit and circuit diagram of a simple electric circuit consisting of a cell and a light bulb connected by wires. **(b)** An open switch is added to the circuit and breaks the closed loop. No current can flow in this circuit and the light is therefore off.

Table 1 Symbols used to represent basic circuit components in circuit diagrams

Circuit component	Circuit symbol
Wire	
Cell (a type of DC voltage source)	
Battery (a series of cells, which is also a DC voltage source)	
A general DC voltage source	
Resistor	
Light bulb	
Switch	
Voltmeter	
Ammeter	

Electrical quantities 1.2.1.2 & 1.2.3.1

OVERVIEW

The quantities of electric charge, Q, potential difference, V, current, I, energy, E, and power, P, are important in our understanding of electric circuits.

THEORY DETAILS

Charge

Electric charge, Q, is a fundamental property of subatomic particles (such as protons and electrons) that is responsible for all electric interactions.

- Charge is measured in coulombs (C) and can be either positive or negative (see Figure 2).
- Charges exert forces on one another without coming into contact. The force between charged particles is called the electrostatic force.
  - Charges with opposite signs attract each other (they pull each other together).
  - Charges with the same signs repel each other (they push each other apart).
- Charge cannot be passed between particles, created or destroyed. It can only be moved through space by the movement of the particles themselves.

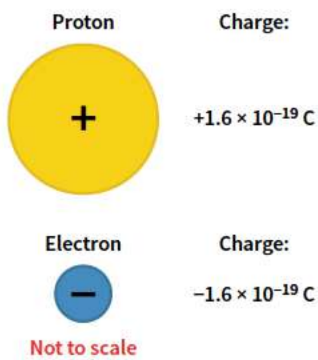


Figure 2 The charges of a proton and electron are fundamental properties of those particles. Notice that these charges are equal and opposite.

- The charge magnitude of the electron and proton is 1.6×10^{-19} C. This charge magnitude is known as the elementary charge, e, because it is the smallest charge that can exist by itself. All other charges are a multiple of this value.
  - The magnitude of a charge is equal to the number of electrons (n_e) or protons (n_p) that make up the charge multiplied by the charge of a single electron or proton.
  - $Q = -n_e e$ or $Q = n_p e$

The term electricity is a general term used to refer to the physical interactions associated with the presence or movement of charge.

Static electricity is the stationary separation or imbalance of electric charge in an object. A build up of static electricity is the reason for the electric shocks (or 'zaps') we sometimes feel when touching materials in our environment.

Some physical interactions can move the charged particles in a material. For example, rubbing a balloon on human hair transfers electrons from the hair onto the rubber balloon.

- Electrons build up on the balloon
  - Electrons are negatively charged
  - The balloon acquires a net negative charge
- There is a loss of electrons from the hair
  - The hair loses negative charge
  - The hair acquires a net positive charge

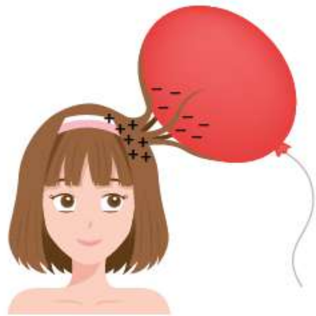


Image: gritsalak karalak/Shutterstock.com

Figure 3 The action of rubbing a balloon on hair transfers electrons from the hair to the balloon.

Since like charges repel each other, a buildup of static charge 'wants' to return to a neutral state. When a statically charged object comes into contact with a material that can conduct charges away from it, the static charge is neutralised through a sudden transfer of charged particles. This is what occurs when we feel an electric shock.

USEFUL TIP

Since 'electricity' is a general term for anything to do with electric charge, avoid using this term when describing specific physical quantities.

Worked example 1

A balloon holds a static charge of −0.30 C before it is neutralised by coming into contact with a grounded wire. Determine the number of electrons (n_e) needed to hold a −0.30 C charge. Take the charge of one electron ($-e$) to be -1.6×10^{-19} C.

Working	**Process of thinking**
$Q = -n_e e$	The total charge is the number of electrons multiplied by the charge of an electron.
$n_e = \frac{Q}{-e} = \frac{-0.30}{-1.6 \times 10^{-19}} = 1.875 \times 10^{18}$	$Q = -0.30$ C, $-e = -1.6 \times 10^{-19}$ C
1.9×10^{18} electrons are needed to hold a –0.30 C charge.	

Static electricity demonstrates the properties and behaviour of charge. The rest of our study on electricity is concerned with moving charge in circuits.

Potential difference

We have learned that charges can attract or repel each other without being in contact. This means that depending on the position of a charge relative to other charges, it has the potential to gain energy when other charges push or pull it.

- The potential of a charged particle to gain energy due to other charges is called electric potential energy.
- The difference in electric potential energy per coulomb between two locations is called the potential difference, V. The symbol ε can also be used to represent potential difference.
- Potential difference is measured in volts (V).
  - Volts are equivalent to joules per coulomb (J C^{-1}).

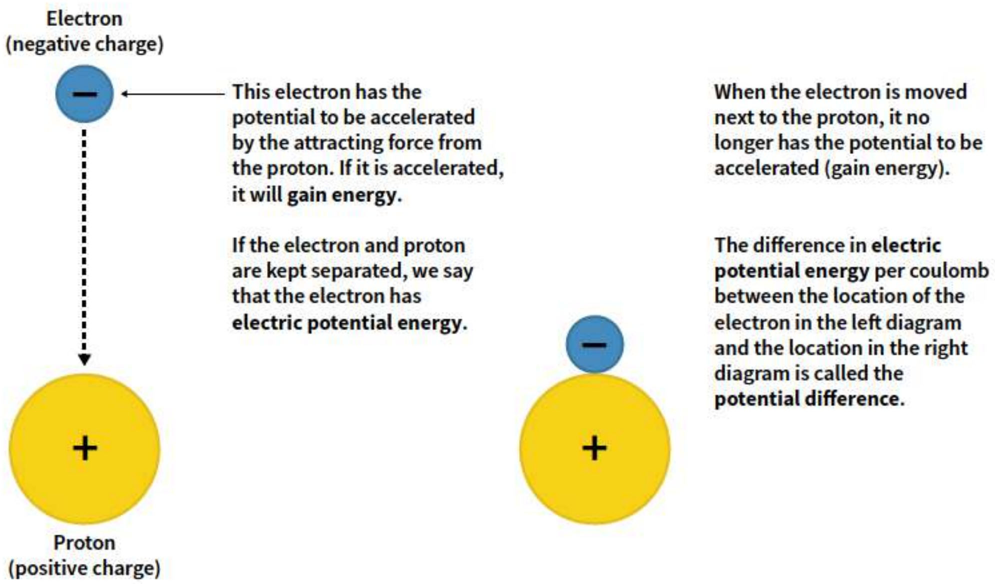


Figure 4 The electric potential energy due to the separation of an electron from a proton shows the concept of potential difference.

$$V = \frac{E}{Q}$$

V = potential difference (V), E = magnitude of difference in electric potential energy between two locations (J), Q = magnitude of charge (C)

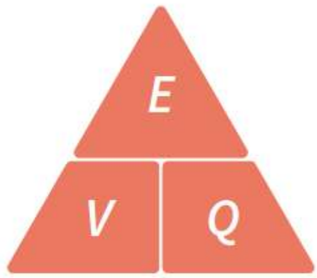


Figure 5 The formula triangle for potential difference

Sources of potential difference

Ideal sources of potential difference – like cells, batteries, and certain power supplies – provide the same potential difference no matter what circuit they are applied to. The potential difference only depends on the source.

One of the common sources of potential difference in electric circuits is a cell. In a cell:

- Charges are separated.
  - Positive charges are at the positive terminal.
  - Negative charges are at the negative terminal.
- Hence there is a difference in electric potential energy (and therefore a potential difference) between the two terminals.

The potential difference of a source is measured from its negative terminal to its positive terminal.

One way to think of how a potential difference is created is to relate it to gravity. The separation of charge in a source is like holding a mass up in the air. Just like charges will not remain separated without a force holding them apart, without something holding it in the air a mass will fall to the ground due to gravity.

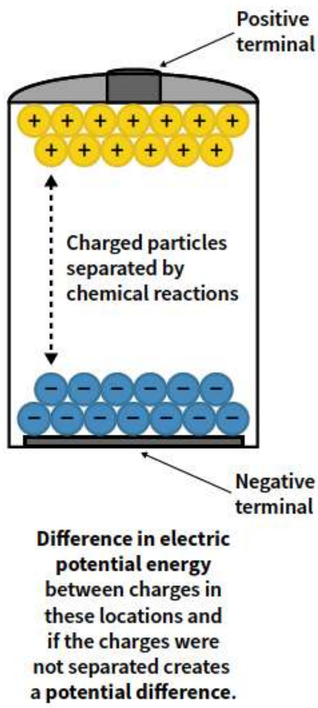


Figure 6 Chemical reactions in a cell separate positive and negative charges between the two terminals.

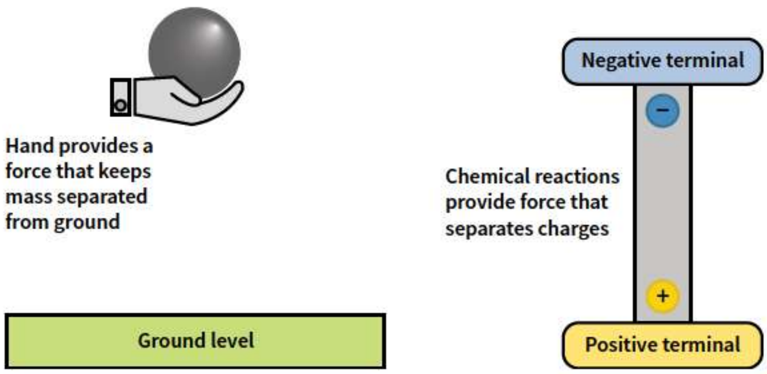


Figure 7 A source separating charges is like holding a mass above the ground.

Worked example 2

When an electron with charge -1.6×10^{-19} C is held at location *X*, away from a positively charged particle, the electron has 2.4×10^{-18} J of electric potential energy. When the electron is at location *Y*, next to the positive particle, it has 0 J of electric potential energy.

a **Determine the potential difference between *X* and *Y*.**

b **If a particle with charge 1.0 C were moved from location *Y* to location *X*, what would be the increase in electric potential energy?**

Working	Process of thinking
a $V = \frac{E}{Q}$ $V = \frac{2.4 \times 10^{-18}}{1.6 \times 10^{-19}}$ $V = 15$ V	*E* is the magnitude of the difference in potential energy between *X* and *Y*: $E = 2.4 \times 10^{-18} - 0 = 2.4 \times 10^{-18}$ J Q is the magnitude of the particle's charge: $Q = 1.6 \times 10^{-19}$ C
b Potential difference is the change in electric potential energy per coulomb, so for one coulomb the change in energy is 15 J OR $V = \frac{E}{Q}$	Use the equivalence of volts, V, and joules per coulomb, J C^{-1}
$15 = \frac{E}{1.0}$ $E = 15$ J	$V = 15$ V, $Q = 1.0$ C

What does the word 'voltage' mean?

A very common word to hear when talking about electricity is 'voltage'. Voltage is a term that is used interchangeably with 'potential difference'. While 'potential difference' reminds us that the quantity describes a difference between locations, the term 'voltage' does not remind us that this quantity is always comparative.

Using 'voltage':

- Using terms like 'voltage across' or 'voltage drop' helps to define the comparison between locations.
  - For example, one might say that the voltage across an AA battery is 1.5 V.
- Whenever a voltage is stated, ensure you can define the two locations across which the potential difference is being measured.

Current

When a potential difference is provided to an electric circuit, it causes an electric current, *I*, to flow. The current at a point is the rate that charge flows past that point.

- The movement of charge requires a physical movement of charged particles.
- The charged particles contributing to a current are called **charge carriers**.
- 'A current' refers to the actual flow of charge carriers.
- Current is measured in amperes (A).
  - Amperes are equal to coulombs per second (C s^{-1}).

If a circuit is not closed (for example, if a switch is open) then current will not flow.

$$I = \frac{Q}{t}$$

I = current (A), *Q* = charge (C), *t* = time (s)

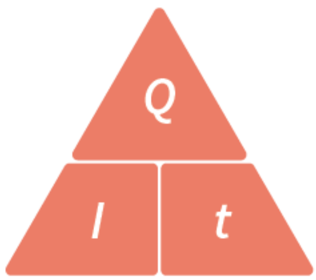


Figure 8 The formula triangle for electric current

Worked example 3

When a battery is connected to a circuit containing a light bulb, 2 C passes through the filament in 0.5 s.

a Determine the current through the filament.

b How much charge would pass through the filament in 10 s if the current remained the same?

Working	**Process of thinking**
a $I = \frac{Q}{t}$	I is the rate of flow of charge over time
$I = \frac{2}{0.5}$ $I = 4$ A	$Q = 2$ C, $t = 0.5$ s
b $I = \frac{Q}{t}$	
$4 = \frac{Q}{10}$ $Q = 40$ C	$I = 4$ A, $t = 10$ s

How a potential difference drives a current

The most common form of electric current is the flow of electrons through metallic wires.

- Electrons are free to move in metallic wires.
- Electrons are repelled from the negative terminal of a cell, as like charges repel.
- Electrons are attracted towards the positive terminal of a cell, as opposite charges attract.
- The result is that the electrons travel from the negative terminal to the positive terminal.

Note that charge carriers (like electrons) are not 'used up' in a circuit. Instead, they transfer their potential energy to the circuit components.

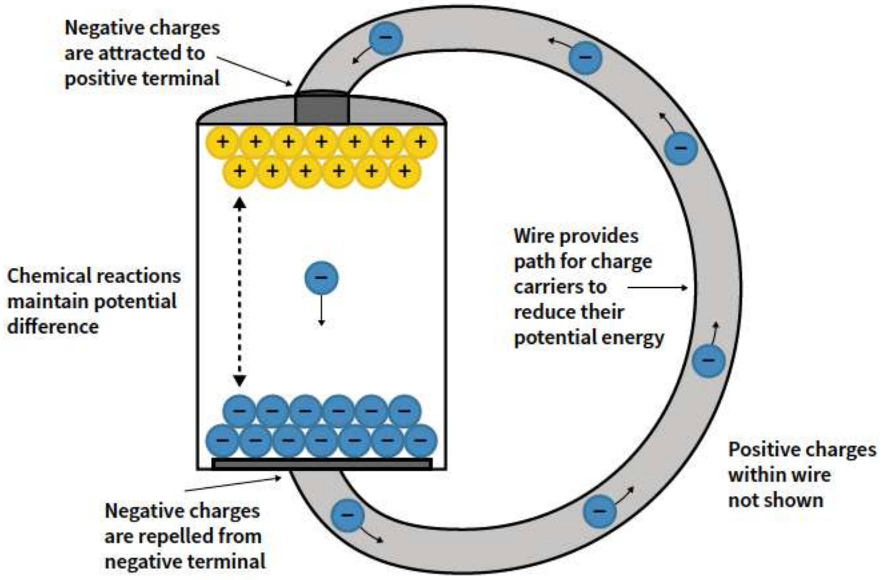


Figure 9 A potential difference provided by a cell causing a current to flow around an electric circuit

While the speed of electrons around a circuit is actually very slow, all of the electrons within the circuit start moving almost instantly when the circuit is closed, so the electric signal travels from one terminal to the other very quickly. This is similar to how water flows. When a tap is turned on, water comes out of the end immediately, even if the water itself is not moving quickly. This is because the pipes are already filled with water, like wires are full of electrons.

Earlier, we introduced the comparison between potential difference and gravity. When a mass being held in the air is released, the force due to gravity will cause it to fall to the ground and reduce its potential energy. Similarly, when a wire connects the terminals of a source, it provides a 'path' (the closed loop – a circuit) for charges to reduce and transfer their potential energy.

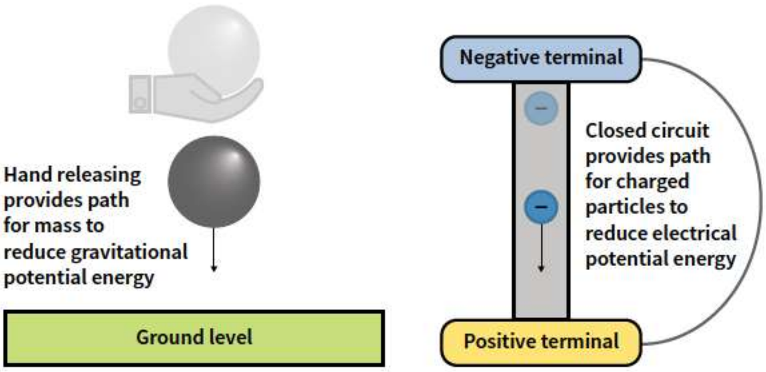


Figure 10 Closing a circuit is similar to allowing a mass to fall to the ground.

Conventional current

Despite current in most circuits being a flow of negative electrons, by convention the direction of current is considered to be the direction that positive charge would flow (or the opposite direction that negative charge flows). This is called **conventional current** and it flows from the positive to the negative terminals of a potential difference source. The direction of electron flow is called the **electron current**. We will use conventional current unless otherwise stated.

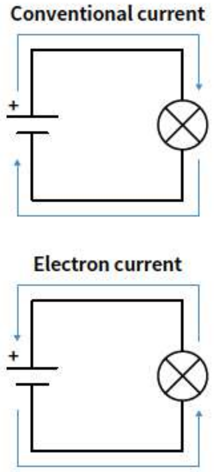


Figure 11 Conventional and electron current directions in a circuit

DC and AC current

Direct current (DC) is current that only flows in one direction around a circuit, whereas alternating current (AC) changes direction. Electrical concepts apply to both forms of current, however our focus will be limited to DC.

Electric potential energy and power

Earlier, we discussed the concept of electric potential energy. Electric potential energy can be transformed into other forms of energy like light, thermal energy, movement, and sound by electrical components.

- Energy, E, is measured in joules (J).

In circuits, we are interested in how much electric potential energy is:

- stored in a source, like a battery.
- delivered (transferred) by a source to a circuit.
- consumed (transformed) by a circuit or individual component.

It is important to understand that energy cannot be created or destroyed, only transformed or transferred. Figure 12 shows how the chemical energy stored inside a battery is delivered as electric potential energy to charge carriers in the wire, which is then consumed by the light bulb in the form of light and thermal energy. At no point is energy created or destroyed.

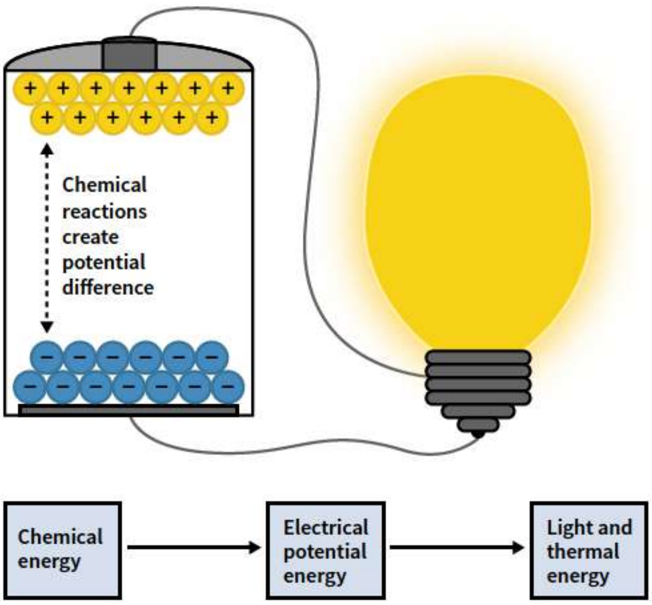


Figure 12 The transformations of energy when a battery is connected in a circuit with a light bulb

[redacted]

Power

Power, P, is the rate of transfer or transformation of energy with respect to time.

- Power is measured in watts (W).
  - Watts are equal to joules per second ($J\ s^{-1}$).
- The total amount of power delivered to a circuit is always equal to the total amount that is consumed by the circuit components.

$$P = \frac{E}{t}$$

P = power (W), E = energy delivered/consumed (J), t = time (s)

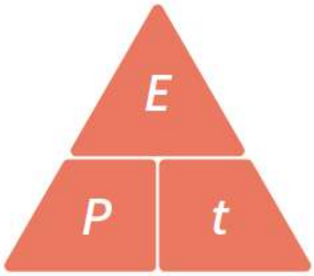


Figure 13 The formula triangle for power

We can formulate another expression for power. Working in SI units:

- Potential difference is the number of joules per coulomb ($J\ C^{-1}$).
- Current is the number of coulombs per second ($C\ s^{-1}$).
- So multiplying potential difference, V, by current, I, gives us the number of joules per second, which is the power, P.
  - $\frac{J}{C} \times \frac{C}{s} = \frac{J}{s}$

$$P = VI$$

P = power (W), V = potential difference (V), I = current (A)

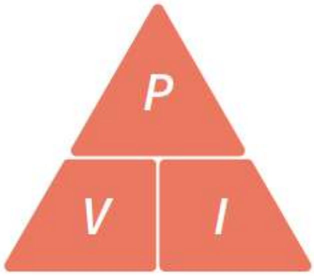


Figure 14 An alternate formula triangle for electric power

USEFUL TIP

When calculating power from current and voltage, make sure the current and voltage you use correspond to the component or components you are calculating the power for.

Worked example 4

Students are investigating an electric circuit.

a It is found that a battery transfers 10 J of electric potential energy to the circuit in 5 s. Determine the average power delivered by the battery.

b During operation, the potential difference across a lightbulb in the circuit is 10 V and a current of 0.10 A is passing through it. Determine the average power dissipated by the light bulb.

c If the battery is the only source, are there any other components in this circuit other than the lightbulb?

	Working	Process of thinking
a	$P = \frac{E}{t}$ $P = \frac{10}{5}$ $P = 2$ W	$E = 10$ J, $t = 5$s
b	$P = VI$ $P = 10 \times 0.10$ $P = 1.0$ W	$V = 10$ V, $I = 0.10$ A
c	Yes.	Total power delivered is equal to the total power consumed. Since all of the battery's power is not being consumed by the lightbulb, there must be other components in this circuit.

The hydraulic circuit analogy 1.2.2.1

OVERVIEW

A common circuit analogy is that of water pipes. Using this analogy clarifies some key electrical concepts.

THEORY DETAILS

A common analogy for an electric circuit is a loop of pipes with flowing water. Figure 15 represents an electric circuit with a source, switch, wires, and a power consuming component. Table 2 shows how components of the hydraulic circuit represent components of an electric circuit.

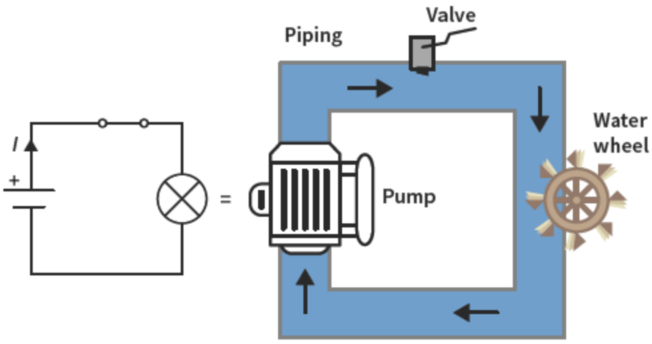


Figure 15 The hydraulic circuit analogy for a circuit containing a source, switch, wires, and a power-consuming component

Table 2 The link between components of the hydraulic circuit analogy and an electric circuit

Hydraulic component	Electric component	Notes
Water pump	Potential difference source (cell, power supply, etc.)	The water pump pushes water around a hydraulic circuit, like a potential difference source drives an electric current.
Piping	Wires	Provide a path for water/charge carriers to flow.
Valve	Switch	Determines whether or not water/current can flow around the circuit
Water wheel	Power consuming component	Uses the energy supplied by the pump/potential difference source.

This analogy models key electrical concepts:

- How the potential difference source drives a current through a circuit.
- A current requires the physical movement of charged particles.
- How components transform energy.

Measuring electrical quantities 1.2.4.1

OVERVIEW

To measure electrical quantities, specialised meters must be used in specific configurations.

THEORY DETAILS

When performing real-world circuit analysis, there are two key quantities we aim to measure.

Measuring potential difference

A voltmeter is used to measure potential difference. To measure the potential difference between two locations, one probe of the voltmeter must be connected to each location. This is known as a 'parallel' connection, and is a measurement **across** the probed locations.

Measuring current

An ammeter is used to measure current. To measure the current through a component, the ammeter must be connected end-to-end in the circuit either before or after that component. This is known as a 'series' connection, and is a measurement **through** the ammeter.

Devices that can be used to measure a range of electrical quantities are called multimeters. To measure a quantity with a multimeter, select the desired quantity on the meter and connect the probes to the circuit the same way a regular meter (a voltmeter or ammeter, for example) would be connected.

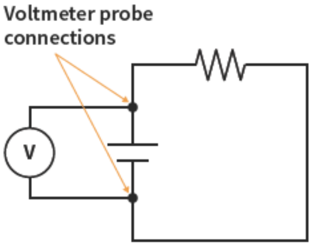


Figure 16 Using a voltmeter to measure the potential difference across a cell in a circuit

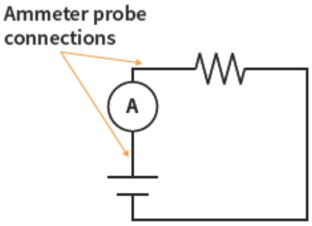


Figure 17 Using an ammeter to measure the current through a cell in a circuit

Theory summary

- Electric circuits are closed conducting loops.
- Electric charge, Q, is a fundamental property of subatomic particles such as electrons.
  - Charge is measured in coulombs (C).
  - Static electricity occurs when there is a stationary separation of charge.
- Potential difference, V, is the change in electric potential energy per unit charge between two locations.
  - $V = \frac{E}{Q}$
  - Potential difference is measured in volts (V).
  - Potential difference is also known as voltage.
- Electric current, I, is the rate that charge flows over time.
  - $I = \frac{Q}{t}$
  - Current is measured in amperes (A).
  - A potential difference 'pushes' or 'pulls' on charged particles, causing a current to flow.
  - Current is not 'used up' around a circuit.
- Electric potential energy, E, can be transformed into many types of energy such as kinetic and thermal.
  - Energy is measured in joules (J).
  - Energy sources like batteries store and deliver potential energy.
  - Energy consumers like light bulbs transform energy.
- Power, P, is the rate of delivery or consumption of energy over time.
  - $P = \frac{E}{t} = VI$
  - Power is measured in watts (W).
- The hydraulic circuit analogy reinforces key electrical concepts.
- Voltmeter probes should be connected in parallel across the locations they are measuring.
- Ammeters should be connected in series with the part of the circuit they are measuring.

KEEN TO INVESTIGATE?

PhET 'Circuit Construction Kit' simulation
phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab

YouTube video: How to Mechatronics – What is Electric Charge and How Electricity Works
youtu.be/iqVtGNQAC2E

CONCEPT DISCUSSION QUESTION

Two batteries with the same milliamp hour (mA h) rating are being used to power two circuits. Circuit *X* draws twice as much current from its battery as Circuit *Y*. Discuss what electrical quantity a mA h rating measures, and explain why the two batteries will run out at different times.

Answers on page 505

Hints

What equation relates the two quantities of milliamp (mA) and hours (h)?

How does the current in a circuit relate to how quickly a battery will run out of charge?

4A Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following best describes the flow of current in an electric circuit?

A Charge flowing around a circuit is passed from particle to particle.

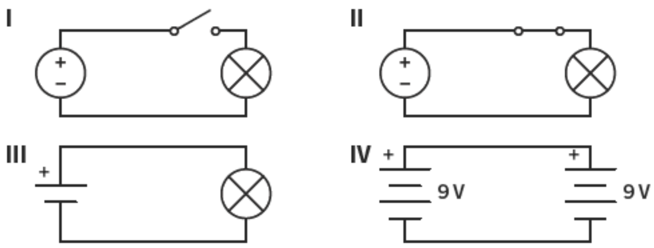
B Charged particles physically flowing around a circuit.

C The separation of charged particles between two points in a circuit.

D The force pushing or pulling charged particles around a circuit.

Question 2

In which of the following circuits would an electric current be flowing? *(Select all that apply)*



Use the following information to answer Questions 3 and 4

Students create a model for an electric circuit using a bakery and its delivery vans. The vans are tightly packed on a circular road. The road has six houses on it.

- Each time they pass the bakery they are loaded full of 6 loaves.
- The vans deliver one loaf to each house.

Question 3

Fill in the gaps in the following paragraphs.

The vans on the road represent the __________ (current/charge carriers/potential difference) in an electric circuit. As the vans pass the bakery they are loaded with fresh bread, which represents how the __________ (electrical source/baker/energy) provides __________ (charge/current/potential energy) to a circuit.

The vans gradually lose their bread around the loop, but they still continue driving. This is similar to how __________ (potential difference/charge/current) decreases around a circuit, but the __________ (potential difference/current) does not get 'used up'.

Question 4

a How is bread distributed to each van at the bakery?

A The first van receives half the bread, the next receives a quarter, and so on.

B The vans receive an equal amount of bread.

C Each van delivers all its bread at the bakery.

b Identify how your answer to part **a** best relates to electric circuits.

A Charge carriers with equal charge magnitude receive an equal amount of electric potential energy.

B The first charge carriers receive more energy.

C Charge carriers transfer all their energy at the battery.

Question 5

A battery is connected to a closed circuit.

Which of the options best describes the energy and power delivered by the battery over 5 minutes? Note that the battery usually lasts for several hours.

	Energy	Power
A	The rate of energy delivered to the circuit with respect to time	The energy used by the circuit
B	The total energy stored inside the battery	The rate of energy delivered to the circuit with respect to time
C	The potential energy from the battery transferred to the circuit over the 5 minutes	The rate of energy delivered to the circuit with respect to time

Question 6

Which of the following properties of an ideal cell are constant regardless of the circuit it is connected to?

A Potential difference

B Power

C Current

DECONSTRUCTED EXAM-STYLE QUESTION

Question 7 (4 MARKS)

When welding metal, large amounts of energy are transferred to heat the metal. A particular weld takes 2.0 s and transfers 400 kJ of energy. The potential difference of the source is 40 kV.

Prompts

a Which equation correctly relates potential difference, energy, and charge?

A $V = \frac{E}{Q}$ **B** $V = EQ$

C $V = \frac{Q}{E}$ **D** $E = \frac{Q}{V}$

b Which equation correctly calculates the number of electrons required to hold a charge of −1.00 C?

A $n_e = \frac{-e}{-1.00} = 1.6 \times 10^{-19}$

B $n_e = \frac{-e}{1.00} = 1.6 \times 10^{19}$

C $n_e = \frac{-1.00}{-e} = 6.25 \times 10^{18}$

D $n_e = \frac{-1.00}{-e} = 6.25 \times 10^{-18}$

Question

c Determine the number of electrons required to provide the magnitude of charge transferred during the weld. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 8 (4 MARKS)

An electric drill that consumes 220 W of power is driven by a 20 V ideal battery.

a What is the operating current of the drill? (1 MARK)

b Jane uses the drill for 12 s to create a hole. How much energy is delivered by the battery to the drill in this period? (1 MARK)

c How many electrons pass through a single point in the drill's circuit during the 12 s? The magnitude of an electron's charge is 1.6×10^{-19} C. (2 MARKS)

Question 9 (1 MARK)

Determine the electric potential energy of a 3.0 C charge after it passes through a 5.0 V phone charger.

Question 10 (5 MARKS)

A cell delivers 10 W of power to an electrical component. The component is replaced with a different device that uses 20 W of power when connected to the cell.

a Determine the time it would take for the replacement component to use the same amount of energy as the first component would in 8.0 s. (2 MARKS)

b Compare the voltage and current of each component. Justify your answer by referencing a property of an ideal source of potential difference. (3 MARKS)

Question 11 (3 MARKS)

Determine the voltage supplied to a light bulb that uses 3.6 kJ of energy every hour and draws 2.0 A of current.

Question 12 (2 MARKS)

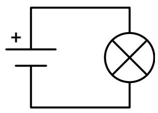
A common cause of power blackouts is a flashover, which occurs when electricity arcs through the air between power lines and surrounding objects. A particular arc lasts 0.50 s and delivers 500 MJ of energy to the ground. Determine the amount of charge transferred from the power line by this arc if the power line voltage is 66 kV.

Question 13 (2 MARKS)

Josie and Kendall are debating how electric current flows. Josie states that current can flow without the physical movement of particles, while Kendall states that current requires the physical movement of charged particles. Who is correct – Josie or Kendall? Explain your answer.

Question 14 (3 MARKS)

Describe the flow of energy from the battery and through the circuit shown in the diagram. Make sure to reference where energy is stored, transferred, and transformed.



Previous lessons

Question 15 (2 MARKS)

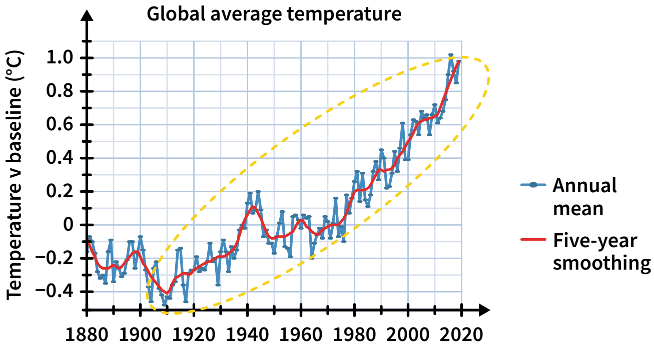
Rady Ation uses a furnace to melt some metal. As it heats up, he observes that it begins to glow.

a Name the type of heat transfer that is causing this glow. (1 MARK)

b State the colour that the metal will first begin to glow. (1 MARK)

Question 16 (2 MARKS)

Determine whether or not the trend circled on this global average temperature versus time graph is a climatic trend. Support your answer with the relevant theory.



Key science skills

Question 17 (5 MARKS)

Cici T. Vee records the current passing through her security camera network at a range of power settings.

Power (W)	Current (mA)
20	94
30	120
50	225
100	420

a Plot Cici's data on a power vs current graph. Include a line of best fit. (3 MARKS)

b Using the graph, determine the voltage at which the camera network is operating. (2 MARKS)

4B RESISTANCE AND OHM'S LAW

Why do some materials conduct electricity better than others? Why do we need wires of different sizes in different circuits? What is a resistor and how does it affect a circuit?

This lesson will introduce the resistivity of materials and the resistance of uniform objects. We will also learn Ohm's law, an important equation that links potential difference, resistance, and the resulting current. Using Ohm's law is an important tool for understanding the circuits introduced in Chapters 4 and 5.

4A What is electricity?	4B Resistance and Ohm's law	4C Series circuits	4D Parallel circuits	4E Combining series and parallel circuits

Study design key knowledge dot point

- model resistance in series and parallel circuits using
  - current versus potential difference (*I*-*V*) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent effective resistance in arrangements in
    - series: $R_T = R_1 + R_2 + ... + R_n$ and
    - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$

Key knowledge units

Electrical resistance	1.2.6.1
Ohm's law	1.2.6.2

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$R = \rho\frac{L}{A}$ resistance
	$V = IR$ Ohm's law

Definitions for this lesson

ohmic device a device that has a constant resistance for all voltages, meaning it follows a linear *I*-*V* relationship

resistance (electrical) a measure of an object's opposition to the flow of electric current

resistivity (electrical) a property of a material describing how much it opposes the flow of electric current

resistor an electrical component that resists the flow of electric current and causes a drop in voltage

Electrical resistance 1.2.6.1

OVERVIEW

Electrical resistance affects the flow of current through a circuit. The resistivity of the material an object is made from and the geometry of the object affect the object's resistance.

THEORY DETAILS

Electrical resistivity

Electrical resistivity, ρ, is an inherent property of a material that measures how much it opposes the flow of current.

- Resistivity is measured in ohm metres (Ω m).
- The microscopic structure of a material determines its resistivity.
- Resistivity is affected by temperature.
- As an inherent property, resistivity does not depend on the geometry (size and shape) of the object made up by the material.

Table 1 The resistivity of some materials at room temperature

Material	Resistivity at 20°C (Ω m)
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Iron	9.70×10^{-8}
Silicon	6.4×10^{2}
Rubber	$\approx 10^{13}$
Polystyrene (type of plastic)	$> 10^{18}$

An electrical **conductor** is a material through which current can flow easily.

- Materials with low resistivity are electrical conductors.
- Metals like copper are good conductors. This is why electrical wires are often made out of copper.

An electrical **insulator** is a material through which current cannot flow easily (having practically no current flow).

- Materials with very high resistivity are electrical insulators.
- Rubber and plastic are good insulators. They are used to coat electrical wires to protect us from coming into contact with the live wire underneath.

A **semiconductor** is a material through which current can only flow easily under certain conditions.

- Materials with resistivity between conductors and insulators are semiconductors.
- Silicon is a commonly used semiconductor.
- The resistivity of these materials can be changed greatly by either changing the temperature of the material or adding impurities to the material.

Electrical resistance

Where resistivity is a measure of a material's opposition to the flow of current, electrical resistance, R, is a measure of an object's opposition to the flow of current. This is similar to the way that density is a property of a material, but mass is a property of an object: two different blocks of steel will have the same density but different masses, just as two different copper wires will have the same resistivity but different resistances.

- Resistance is measured in ohms (Ω).
- Resistance depends on the object's material and geometry (size, shape).

For solid, uniform objects:

$$R = \rho \frac{L}{A}$$

R = resistance (Ω), ρ = resistivity (Ω m), L = length in direction of current (m), A = cross-sectional area (m^2)

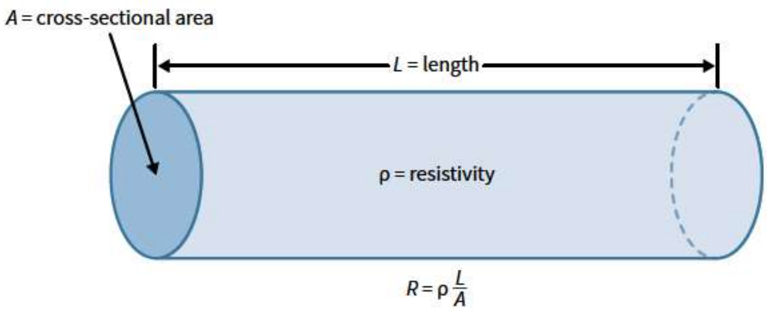


Figure 1 The material and geometry (shape) of an object determines its resistance.

A **resistor** is an electrical component that is used in a circuit to limit the flow of current. It is often necessary to limit current in a circuit to protect components from burning out.

- Resistors convert the electric potential energy of charge carriers flowing through them into thermal energy.
- Resistors are often made from long coils of wire or from materials like carbon and metal oxide films.
- The resistance rating of common resistors is denoted by their colour bands.

It is helpful to model other electrical components like lightbulbs, heaters, and even devices like phone chargers as resistors to complete circuit analysis.

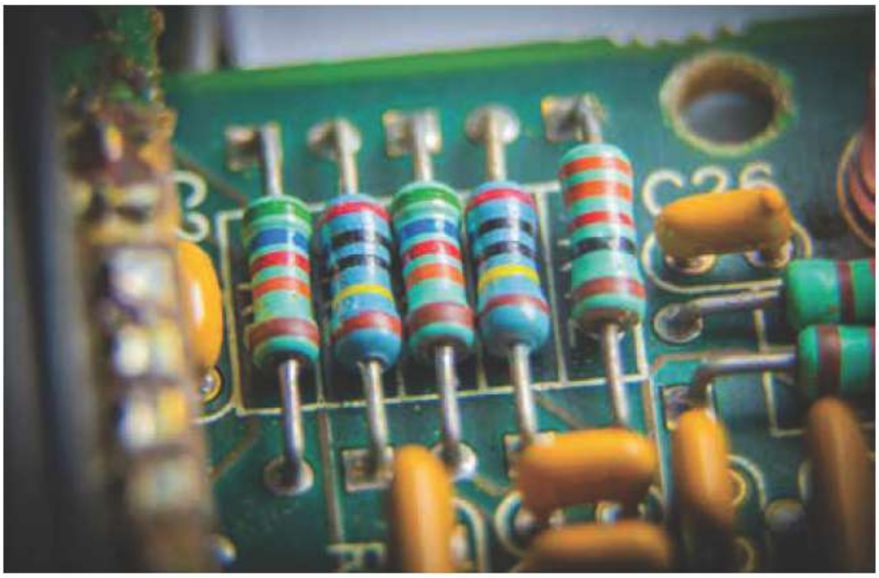


Image: TonStocker/Shutterstock.com

Figure 2 Resistors in a circuit. Their resistance rating is denoted by their colour bands.

Worked example 1

A 1.5 m long cylindrical wire has a radius of 1.0 mm. It is made of solid gold, which has a resistivity of $2.3 \times 10^{-8}\ \Omega$ m.

a Determine the resistance of the wire.

b Is gold an electrical conductor or insulator? Justify your answer.

Working	Process of thinking
a $1.0 \text{ mm} = 1.0 \times 10^{-3}$ m	Convert radius from mm to m.
$A = \pi r^2 = \pi \times (1.0 \times 10^{-3})^2 = 3.14 \times 10^{-6}\ \text{m}^2$	Calculate the cross-sectional area of the wire (the cross-section of a cylinder is a circle).
$R = \rho \frac{L}{A} = 2.3 \times 10^{-8} \times \frac{1.5}{3.14 \times 10^{-6}}$ $R = 1.1 \times 10^{-2}\ \Omega$	Substitute $A = 3.14 \times 10^{-6}\ \text{m}^2$, $\rho = 2.3 \times 10^{-8}\ \Omega$ m, $L = 1.5$ m into the resistance formula.
b [Gold is an electrical conductor[1]][since it has very low resistivity.[2]]	Explicitly address whether gold is a conductor or insulator.[1] Use the relevant theory: electrical resistivity.[2]

Ohm's law 1.2.6.2

OVERVIEW

Ohm's law defines the relationship between the potential difference across an electrical component, V, the current through the component, I, and the resistance of the component, R.

THEORY DETAILS

Ohm's law provides the basis of circuit analysis. This equation allows us to determine the amount of current that will flow through a circuit if we apply a certain potential difference.

$V = IR$

V = potential difference (V), I = current (A), R = resistance (Ω)

Note that the relationship between current and potential difference indicated by Ohm's law is positive and linear. This means that if a higher potential difference is applied across a resistor, a higher current will flow.

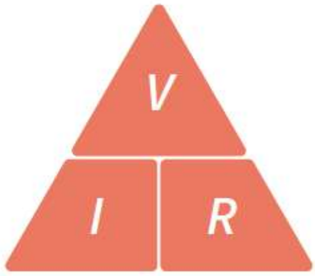


Figure 3 The formula triangle for Ohm's law

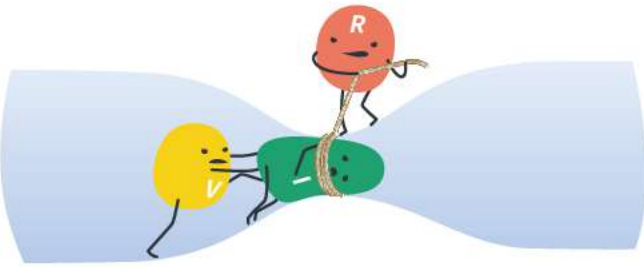


Figure 4 An illustrative representation of Ohm's law

Ohmic devices

An ohmic device is an electrical component that has a constant resistance for all voltages. In other words, ohmic devices have a constant resistance that is independent of the applied voltage.

- Resistors are ohmic devices.
- Despite often being modelled as resistors, many light bulbs are non-ohmic devices.

***I-V* graphs**

An effective tool to describe the operation of an electrical component is to graph the relationship between the potential difference, V, across the component and the current, I, flowing through it.

In an I-V graph, the resulting current is plotted for a range of voltages.

- Voltage is on the horizontal axis since it is the independent variable (the potential difference drives the current).
- Current is on the vertical axis since it is the dependent variable.

Rearranging Ohm's law into the form $R = \frac{V}{I}$ shows that resistance is the ratio of potential difference to current.

- An ohmic device will have a linear I-V graph (constant gradient) since it has a constant resistance.
  - I-V graphs of ohmic devices always pass through the origin since there is no potential difference to drive a current.
  - The gradient is equal to the reciprocal of resistance: $gradient = \frac{I}{V} = \frac{1}{R}$
- A non-ohmic device will have a non-linear I-V graph (varying gradient) since it has a varying resistance.

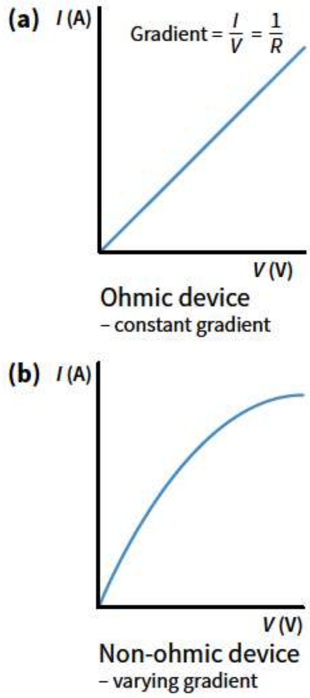


Figure 5 The I-V graphs of **(a)** an ohmic device and **(b)** a non-ohmic device

Worked example 2

When a potential difference of 60 V is applied across a resistor, a 2.0 A current is measured to pass through it.

a Determine the resistor's resistance at this voltage.

b Assuming the resistor is an ohmic device, what potential difference would drive a 0.50 A current through the resistor?

Working	Process of thinking
a $V = IR \therefore 60 = 2.0 \times R$ $R = \frac{60}{2.0} = 30\ \Omega$	Substitute $V = 60$ V and $I = 2.0$ A into Ohm's law.
b $V = IR = 0.50 \times 30$ $V = 15$ V	The resistor is an ohmic device so its resistance is constant. Substitute $R = 30\ \Omega$ and $I = 0.50$ A into Ohm's law.

Theory summary

- **Resistivity**, ρ, is how much a material opposes the flow of current.
  - Resistivity is an inherent property of a material that does not depend on geometry.
  - It is measured in ohm metres (Ω m).
  - Materials can be either **conductors**, **insulators**, or **semiconductors** depending on their resistivity.
- **Resistance**, R, is how much an object opposes the flow of electric current.
  - Resistance depends on an object's material and geometry.
  - It is measured in ohms (Ω).
  - For a uniform object: $R = \rho \frac{L}{A}$
- A **resistor** is an electrical component used to add resistance to a circuit.
  - Resistors dissipate thermal energy.
- **Ohm's law** tells us that for a given resistance, applying a greater potential difference will drive a greater current.
  - $V = IR$
  - An ohmic device has a constant resistance for all voltages.
- Resistance is the ratio of current to potential difference.
  - *I-V* graphs of ohmic devices are linear so they have a constant gradient.
  - The gradient of an *I-V* graph for an ohmic device is $\frac{1}{R}$.
  - *I-V* graphs of non-ohmic devices are non-linear so they have a varying gradient.

KEEN TO INVESTIGATE?

Boston University 'Ohm's law' simulation
physics.bu.edu/~duffy/HTML5/ohm_IVgraph.html

PhET 'Ohm's law' simulation
phet.colorado.edu/en/simulation/ohms-law

YouTube video: SparkFun Electronics – Ohm's law
youtu.be/8jB6hDUqN0Y

YouTube video: The engineering mindset – Ohm's law explained
youtu.be/HsLLq6Rm5tU

Hyperphysics – Microscopic view of Ohm's law
hyperphysics.phy-astr.gsu.edu/hbase/electric/ohmmic.html

CONCEPT DISCUSSION QUESTION

Components in common circuits have resistances that generally range in magnitude from ohms to megaohms ($\times 10^6$ Ω). Discuss whether it is important to consider the resistance of the wires connecting the components when analysing these circuits. Discuss how your answer might change if the wires in the circuit were extremely long or extremely thick?

Answers on page 505

Hints

How do the resistances compare between standard resistors and conducting wires?

What quantities would be affected by considering the additional resistance of the wires?

How does length affect wire resistance?

How does thickness (cross-sectional area) affect wire resistance?

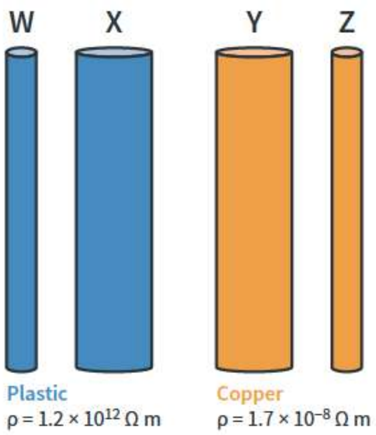
[redacted]

4B Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–3.

Mary and Joseph have been given four different objects for Christmas. They are shown here, along with the resistivities of both materials.



Question 1

In which of the following situations could the resistivities of the two copper objects (Y and Z) be different?

A The objects were cut to different lengths.

B The objects were heated to different temperatures.

C One of the objects was curved.

Question 2

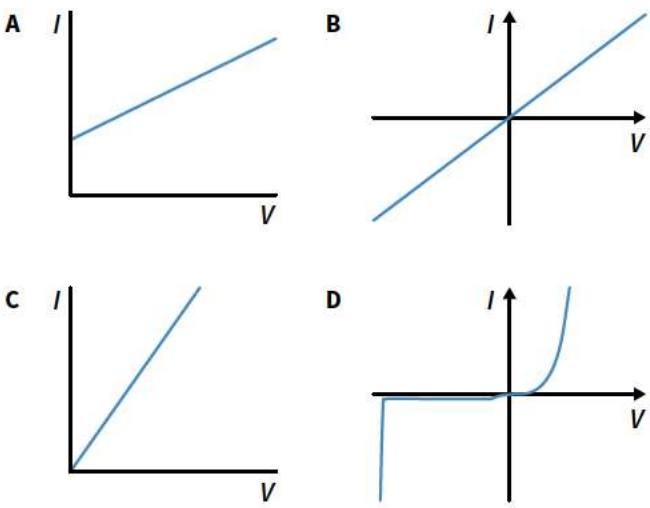
Mary wants to pick the object with the lowest resistance (measured lengthwise). Which object should Mary choose?

Question 3

Joseph wants to pick the object with the highest resistance (measured lengthwise). Which object should Joseph choose?

Question 4

Which of the following *I-V* graphs represent an ohmic device? *(Select all that apply)*



Question 5

Identify which of the properties listed below affect resistivity and which affect resistance by ticking relevant parts of the table.

Property	Affects resistivity?	Affects resistance?
Length		
Cross-sectional area		
Material		
Temperature		

Question 6

Which of the following statements about a resistor is incorrect?

A A resistor dissipates energy in the form of thermal energy.

B A resistor provides energy to a circuit.

C A resistor limits the current in a circuit.

D A resistor reduces the rate of movement of charge with respect to time.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 7 (2 MARKS)

Students are provided with an unknown resistor that has a constant resistance for all potential differences. The students are instructed to plot an *I-V* graph for the resistor.

Prompts

a What is a device that has a constant resistance for all potential differences called?

A Constant current device

B Non-ohmic device

C Ohmic device

D Constant voltage device

b Which of the following best describes the gradient of an *I-V* graph for such a device?

A Negative and constant

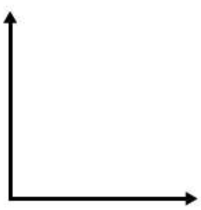
B Positive and constant

C Positive and varying

D Negative and varying

Question

c Using the axes provided, sketch the *I-V* graph you would expect for the resistor. Your sketch does not need to include values, but axis labels and appropriate units should be included. (2 MARKS)



EXAM-STYLE QUESTIONS

This lesson

Question 8 (2 MARKS)

A cylindrical copper wire to be used inside an electric motor is 0.30 m long with a radius of 2.0×10^{-3} m. The resistivity of copper is 1.7×10^{-8} Ω m. Determine the resistance of this wire.

Question 9 (1 MARK)

When a 12 V potential difference is applied across a resistor, it drives a current of 0.20 A. Determine the resistor's resistance.

Question 10 (4 MARKS)

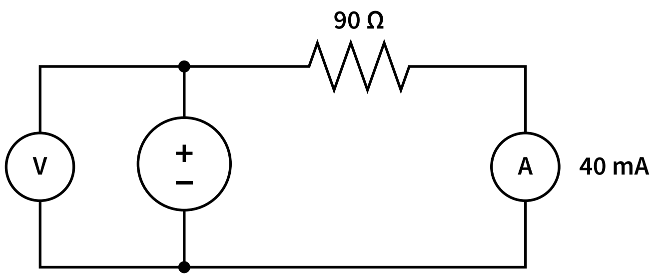
A graphite electrode used in an arc furnace has a diameter of 60 cm, a length of 2.4 m, and is known to have a resistance of 12 μΩ.

a Determine the resistivity of the graphite in this electrode. (3 MARKS)

b Determine the current when a potential difference of 900 V is applied across the electrode. (1 MARK)

Question 11 (2 MARKS)

A current of 40 mA is measured by the ammeter in this circuit.



Determine the potential difference that will be measured by the voltmeter.

Question 12 (2 MARKS)

When an ohmic device with resistance *R* is connected to an ideal source with potential difference *V*, a current of *I* flows through it.

a If the potential difference were to triple what would the resulting current be? (1 MARK)

A I

B $2I$

C $\frac{1}{3}I$

D $3I$

b If the resistance were to double, what would the potential difference across the device be? (1 MARK)

A $\frac{1}{2}V$

B $\frac{1}{4}V$

C V

D $2V$

Question 13 (2 MARKS)

A piece of a wire has a resistance of 12 Ω.

a What would be the resistance of two of these pieces if they were placed side by side (in parallel)? (1 MARK)

b What would be the resistance of the piece of wire if it were three times as long? (1 MARK)

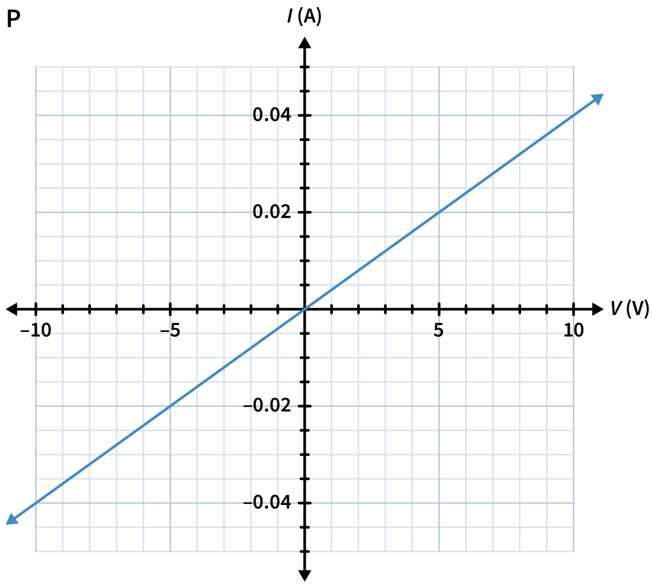
Question 14 (2 MARKS)

3.0 A of current flows through an ohmic phone charger when an ideal 60 V source is connected. Determine the current that would flow through the charger if it was connected to an ideal 45 V source.

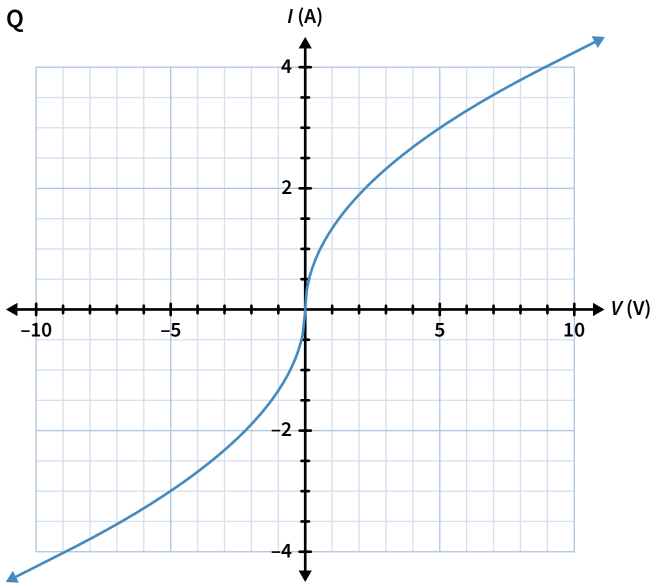
Question 15 (6 MARKS)

I-V graphs are produced for two electrical devices P and Q.

P



Q



a Which of the devices is ohmic? (1 MARK)

b Use the graph for device P to determine its resistance. (3 MARKS)

c Use Ohm's law to determine the resistance of device Q when the voltage applied is 5 V. (2 MARKS)

Question 16 (4 MARKS)

Compare the quantities resistivity and resistance. Your answer should reference what each term measures and the factors that affect each term.

Previous lessons

Question 17 (2 MARKS)

A sample of lead is heated to 1700°C and is glowing red. By modelling the sample as a black body, calculate the λ_{max} of the radiation emitted. Take Wien's constant b to be 2.89×10^{-3} m K.

Question 18 (2 MARKS)

The spectrum of electromagnetic radiation is divided into X-rays, visible light, infrared, radio waves, gamma rays, microwaves, and ultraviolet. List these types of radiation from

a longest to shortest wavelength. (1 MARK)

b highest energy to lowest energy. (1 MARK)

Key science skills

Question 19 (6 MARKS)

Elle Ektrik is experimenting with two resistors of unknown resistance. She produces the following data with a high level of confidence:

	Current (mA)	
Voltage (V)	**Resistor 1**	**Resistor 2**
1.5	70	40
3.0	160	80
4.5	230	110
6.0	280	150

a Plot the data on an *I*-*V* graph. Be sure to include axis labels, appropriate units, and lines of best fit. Label each line of best fit with the corresponding resistor number. (5 MARKS)

b Without using calculations, determine which resistor has a greater resistance. (1 MARK)

4C SERIES CIRCUITS

We have learned about electrical quantities and how they interact in an electrical component. But how do electric circuits behave when we add multiple components? In this lesson, we will introduce the series (end to end) connection of components and how voltage, current, and power behave in a series circuit.

4A What is electricity?	4B Resistance and Ohm's law	4C Series circuits	4D Parallel circuits	4E Combining series and parallel circuits

Study design dot points

- model resistance in series and parallel circuits using
  - current versus potential difference (I–V) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent effective resistance in arrangements in
    - series: $R_T = R_1 + R_2 + \ldots + R_n$ and
    - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
- compare power transfers in series and parallel circuits

Key knowledge units

Equivalent resistance in series circuits	1.2.6.3
Series circuit analysis	1.2.9.1

Formulas for this lesson

Previous lessons		New formulas
4A	$P = VI$	$R_T = R_1 + R_2 + \ldots + R_n$ equivalent series resistance
4B	$V = IR$	

Definitions for this lesson

equivalent resistance the effective resistance when two or more resistive components are treated as one component

series circuit an electric circuit that has only series connections

series connection a connection of components from end to end

Equivalent resistance in series circuits 1.2.6.3

OVERVIEW

A series circuit contains components that are all connected end to end. The equivalent resistance of series resistors is the sum of their individual resistances.

THEORY DETAILS

Series circuits

Components in series are connected end to end, either directly or by conducting wires. When all the components in a circuit are connected in series, this is called a series circuit. Figure 1 shows two examples of series circuits.

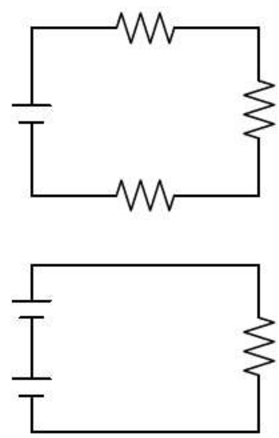


Figure 1 Two series circuits

The order of components in a series circuit does not matter. That means that components can be rearranged in a circuit and the behaviour of the circuit will remain the same. When solving problems with complex series circuits, reordering components can help to make circuits appear more familiar.

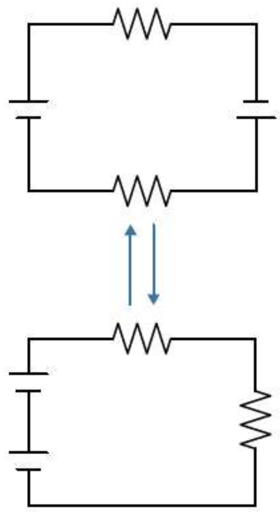


Figure 2 The order of components in a series circuit does not affect their behaviour.

Equivalent resistance

A useful circuit analysis tool is to find the equivalent resistance, R_T, of multiple resistive components. Combining multiple components together into one equivalent component allows us to calculate current and voltage across a whole circuit with Ohm's law. For resistors in series, the equivalent resistance is equal to the sum of each individual resistance.

$$R_T = R_1 + R_2 + \ldots + R_n$$

R_T = equivalent series resistance (Ω), R_n = individual resistance of component n (Ω)

Note that you can calculate an equivalent resistance for any number of resistors. For example, in Figure 3, R_1 and R_2 could be combined so that the circuit effectively has two resistors.

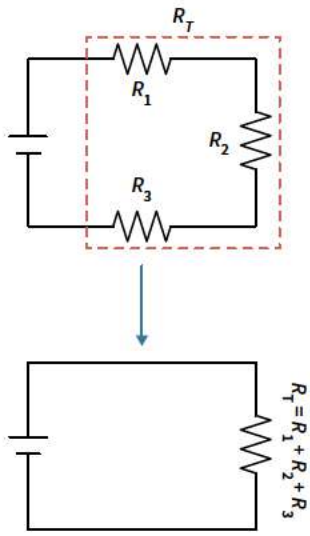


Figure 3 Replacing a number of series resistors with one equivalent resistance

Series circuit analysis 1.2.9.1

OVERVIEW

Series circuit analysis allows us to calculate the behaviour of series circuits. We will use Ohm's law to determine the relationship between the current, voltage, and power around series circuits.

THEORY DETAILS

Current in series circuits

In a series circuit there is only one path for current to flow. We also know that in electric circuits, charge cannot build up at any point. This means that the current is equal at all points around a series circuit. This is similar to how the flow rate of water in a loop of pipe is the same at all points around the pipe, since the water cannot build up at any points around the loop.

The current in a series circuit is determined by the total voltage being supplied, V_T, and the equivalent resistance of the whole load, R_T, using Ohm's law.

$$I = \frac{V_T}{R_T}$$

We can see that the current in a series circuit will increase with a greater supplied voltage and decrease with a greater equivalent resistance.

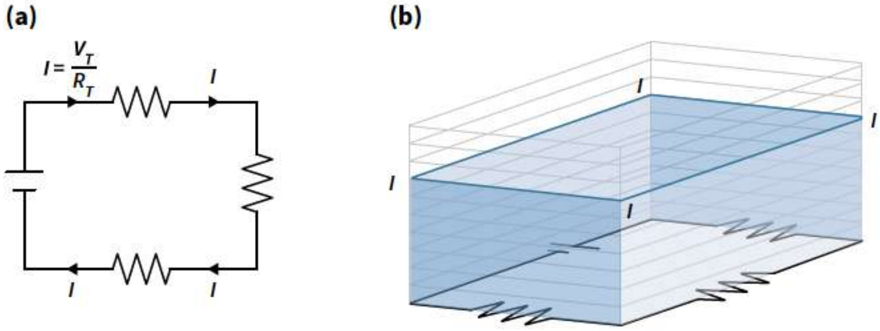


Figure 4 **(a)** A series circuit and **(b)** the associated current around the circuit

Voltage in series circuits

In series circuit analysis, we must understand some key points about voltage.

- The voltage supplied to a series circuit, V_T, is the sum of the voltages supplied by each source in the circuit.
  - Many electric devices such as toys and portable radios connect multiple 1.5 V AA or AAA batteries in series to supply their circuits with a higher voltage.
- The voltage drop across the entire load is the sum of the voltage drops across each component in the load, $V_{load} = V_T = V_1 + V_2 + \ldots + V_n$.

- The voltage drop across the load of the circuit is always equal to the voltage supplied. This is why we can use the equation $V = \frac{V_T}{R_T}$ to determine current, since $V_{load} = V_T$ and R_T represents the load.

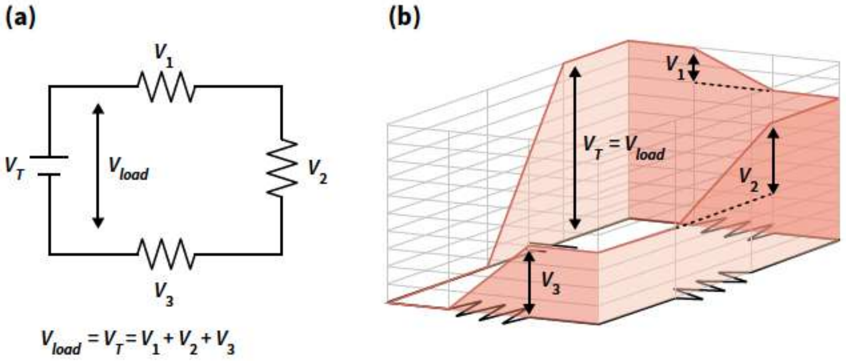


Figure 5 **(a)** A series circuit and **(b)** the changes in voltage around the circuit. The total voltage dropped is equal to the voltage supplied.

The voltage drop across any load component can be found with Ohm's law: $V_n = IR_n$.

Since the current is the same through each load component, the voltage drop across each component is proportional to its resistance.

$$V_n \propto R_n$$

An equivalent way of writing this statement is $\frac{V_n}{V_T} = \frac{R_n}{R_T}$. This means that in a series circuit with multiple components, there will be a greater voltage drop across the higher resistance components. Remember that the sum of all the voltage drops will still equal the total supply voltage.

Power in series circuits

In series circuits, the total power delivered by sources is equal to the total power used by the load.

$$P_T = V_T I$$

When determining the power delivered or used by a single component, the correct voltage value must be used in the power equation.

- For a source, the voltage used to calculate the power supplied is the voltage supplied by that source.
- For a load component, the voltage used to calculate the power used is the voltage drop across that component.

When we add more resistance to a series circuit, we decrease the current through the circuit since the supplied voltage remains constant. Therefore, adding resistance causes the amount of power delivered to and used by a circuit to **decrease**.

- This means that adding more components/devices in series causes the power of each device to drop.
- This effect is often undesirable, so series circuits are not always the best choice when designing electrical systems.

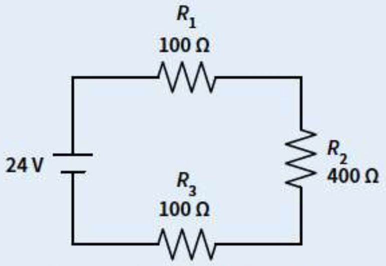
USEFUL TIP

When you calculate the voltage drop across a single component in a series circuit, make sure that your answer:

1. is smaller or equal to the supply voltage, and
2. follows the proportional relationship between resistance and voltage $V_n \propto R_n$

Worked example 1

An ideal cell is delivering power to a series circuit containing three resistors.



a Determine the equivalent resistance of the three resistors.

b What is the voltage drop across this equivalent resistance?

c What is the current through the cell?

d What is the power being dissipated by the resistor R_3?

Working	Process of thinking
a $R_T = R_1 + R_2 + R_3$ $R_T = 100 + 400 + 100 = 600\ \Omega$	The equivalent series resistance is the sum of each individual resistance.
b $V_{load} = V_T = V_{cell} = 24\text{ V}$ The voltage drop across the equivalent resistance is 24 V.	The total voltage drop across the load will be equal to the total voltage supplied. Here the equivalent resistance is the total load.
c $V_T = IR_T$ $24 = I \times 600$ $I = 0.040\text{ A}$	Current is equal all around a series circuit. Use Ohm's law for the equivalent resistance to determine current: $V_T = 24\text{ V}$, $R_T = 600\ \Omega$
d $V_3 = IR_3 = 0.040 \times 100$ $V_3 = 4.0\text{ V}$ $P_3 = V_3 I = 4.0 \times 0.040$ $P = 0.16\text{ W}$	Current through R_3 is the same as through the cell. Find voltage drop across R_3 using Ohm's law: $I = 0.040\text{ A}$, $R_3 = 100\ \Omega$ Use the voltage drop across R_3 and the current through R_3 to determine the power dissipated by R_3.

Theory summary

- Components in series are connected end to end.
- Series circuits only contain series connections.
- The equivalent resistance of resistors in series is the sum of their individual resistances.
  - $R_T = R_1 + R_2 + \ldots + R_n$
  - Calculating equivalent resistance is an important circuit analysis tool.
- Current is equal at all points in a series circuit.
  - The supply voltage and total equivalent resistance of a circuit determines the current.
- The voltage supplied to a series circuit is equal to the voltage dropped across the load.
  - The total voltage supplied to a series circuit is the sum of each source's individual voltage.
- Voltage drop across each series component is proportional to its resistance.
  - $V_n \propto R_n$
- The power used by series circuits decreases as more components (and hence more resistance) are added.

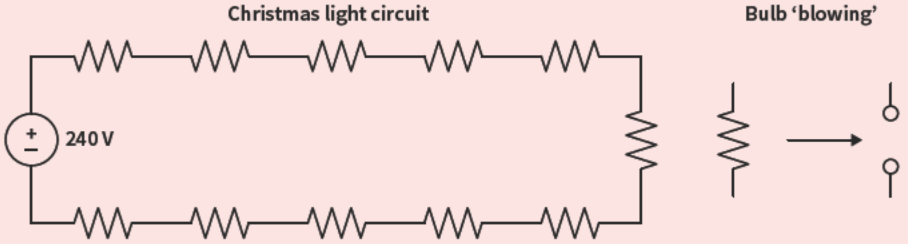
KEEN TO INVESTIGATE?

PhET 'Circuit Construction Kit' simulation
phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab

YouTube video: The Engineering Mindset – DC series circuits explained
youtu.be/VV6tZ3Aqfuc

CONCEPT DISCUSSION QUESTION

A set of Christmas lights are all connected in series to a 240 V ideal DC source as shown. When a light 'blows', the electrical connection inside the bulb is broken and the device becomes a gap in the circuit.



Discuss how the power consumption of each existing bulb would change if, first, another bulb was connected to the circuit in series, and then one of the bulbs blew.

Answers on page 505

Hints

How does adding a component affect the total equivalent resistance?

How does a change in resistance affect the current through a series circuit?

What factors affect the power consumption of each bulb?

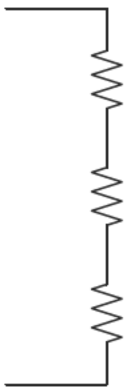
4C Questions

THEORY REVIEW QUESTIONS

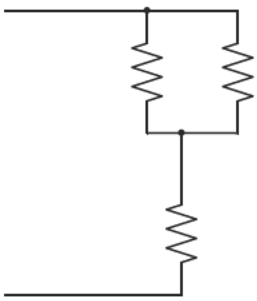
Question 1

Which of the following sets of components are connected only in series? (*Select all that apply*)

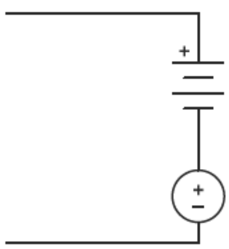
I



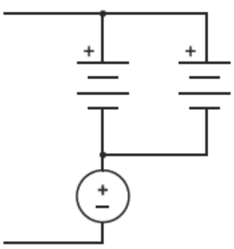
II



III

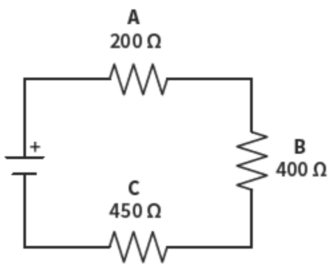


IV



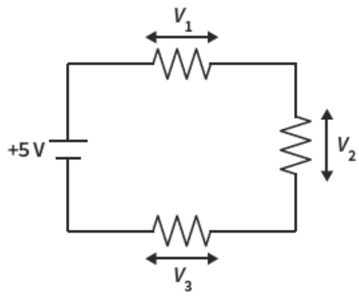
Question 2

Determine which resistor in the circuit shown would have the largest voltage drop across it.



Question 3

Which of the following equations is true for this circuit?



A $V_1 = 5\text{ V}$

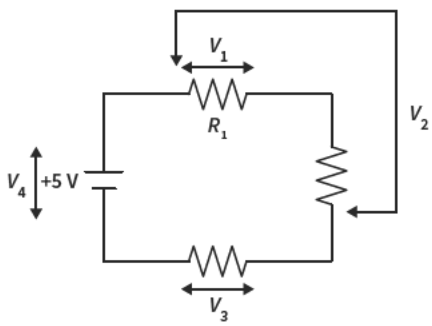
B $V_2 = 5\text{ V}$

C $V_1 + V_2 = 5\text{ V}$

D $V_1 + V_2 + V_3 = 5\text{ V}$

Question 4

Which of the four voltages shown below should be used when calculating the power used by resistor R_1?



Question 5

Which of the following statements about series circuits is **incorrect**?

A All components in a series circuit are connected end to end.

B Adding more components to a series circuit will increase the total power transferred to the circuit.

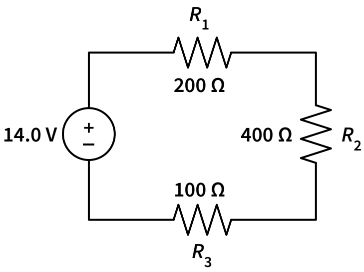
C The voltage drop across individual series resistors follows Ohm's law.

D The current at all points in a series circuit is equal.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 6 (4 MARKS)

Students are experimenting with the series circuit shown.



Prompts

a What is the relationship between the current going through each resistor?

A Equal

B Proportional to resistance

C Inversely proportional to resistance

D Not enough information to determine

b What is the equivalent resistance of the three resistors?

A 57 Ω

B 400 Ω

C 700 Ω

D 1400 Ω

c What is the current through R_3?

A 0.200 A

B 0.0200 A

C 0.140 A

D 0.0140 A

d What is the voltage drop across R_3?

A 20.0 V

B 2.00 V

C 14.0 V

D 1.40 V

Question

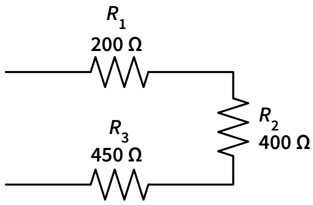
e Determine the power dissipated by R_3. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 7 (2 MARKS)

Three resistors are connected in series.

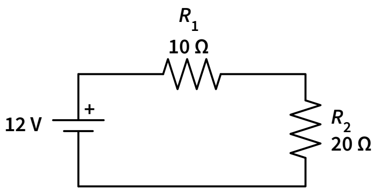


a What is the equivalent resistance of the series resistors shown? (1 MARK)

b What is the equivalent resistance of resistors R_2 and R_3? (1 MARK)

Question 8 (3 MARKS)

An ideal cell provides 12 V to the series circuit shown.

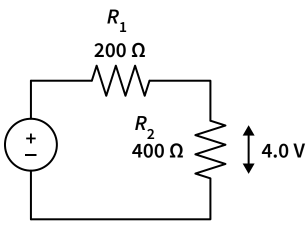


a Determine the current through the circuit. (2 MARKS)

b Determine the voltage drop across R_2. (1 MARK)

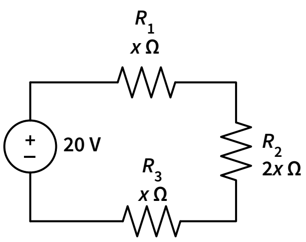
Question 9 (3 MARKS)

Determine the voltage of the DC supply in this circuit. The voltage drop across R_2 is 4.0 V.



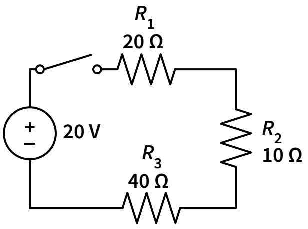
Question 10 (3 MARKS)

A 20 V DC source is connected to the circuit shown. Determine the voltage drops across each of R_1, R_2, and R_3.



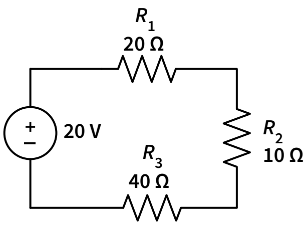
Question 11 (1 MARK)

Determine the power dissipated by the resistor R_2 in the circuit shown.



Question 12 (5 MARKS)

The following circuit is being tested.

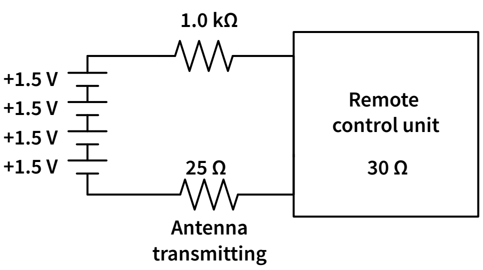


a What is the power delivered by the DC voltage source? (3 MARKS)

b What is the power consumed by R_3? (2 MARKS)

Question 13 (9 MARKS)

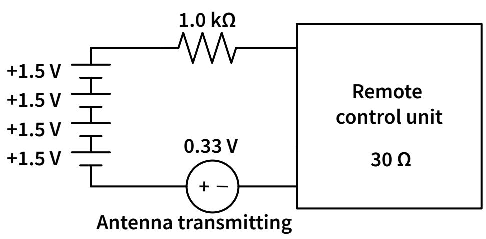
Four 1.5 V AA cells are powering the circuit of a remote controlled toy. In this configuration, the toy's antenna is transmitting information. The remote control unit will overheat if a current greater than 7.00 mA flows through it.



a Will the unit overheat in the configuration shown? (3 MARKS)

b The 1.0 kΩ resistor stops working and needs to be replaced. Four replacement resistors are available with resistances of 800 Ω, 810 Ω, 820 Ω, or 830 Ω. Determine the resistor with minimum resistance that will prevent the control unit from overheating. (3 MARKS)

c When the antenna is receiving information, it can be modelled as a 0.33 V DC voltage source rather than a resistor, as shown.



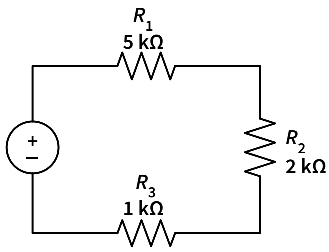
What is the power delivered to the circuit by the antenna? Give your answer in mW. (3 MARKS)

Question 14 (3 MARKS)

Sione and Bruno are debating the effect of adding resistive components on the power usage of a series circuit. Sione says that adding components will decrease the power used, whereas Bruno says that it will increase power use. Evaluate both claims and state who is correct.

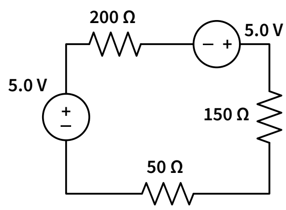
Question 15 (2 MARKS)

A DC source delivers 10 W to this series circuit. Determine the power dissipated by R_3 to three significant figures.



Question 16 (6 MARKS)

A circuit containing two DC sources and three resistors is shown below.



a Determine the power delivered by each source. (3 MARKS)

b Draw an equivalent circuit which has only one source, V_T, and one resistor, R_T. Label each component and include the values of V_T and R_T. (2 MARKS)

c What would happen to the power delivered by each source if the position of the 200 Ω resistor and a source were swapped? (1 MARK)

Previous lessons

Question 17 (2 MARKS)

Explain why the solid rock in the Earth's mantle can convect. Comment on the speed of the convection.

Question 18 (2 MARKS)

Determine the voltage supplied to a light bulb that uses 7.2 kJ every hour and draws 1.0 A of current.

Key science skills

Question 19 (2 MARKS)

Mahua is investigating the effect of increasing resistance on power delivery in series circuits. She connects an ideal cell to an increasing number of resistors, each having equal resistance. Each time Mahua connects another resistor, she records the current through the circuit **once** and proceeds with adding the next resistor. Explain how a change to Mahua's experiment could decrease the effect of random error on her results.

4D PARALLEL CIRCUITS

As well as being connected in series, electrical components can be connected in parallel. Parallel circuits have important uses such as in household circuits and electronic devices. In this lesson we will analyse parallel connections and how voltage, current, resistance, and power behave in a parallel circuit.

4A What is electricity?	4B Resistance and Ohm's law	4C Series circuits	4D Parallel circuits	4E Combining series and parallel circuits

Study design dot points

- model resistance in series and parallel circuits using
  - current versus potential difference (I-V) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent effective resistance in arrangements in
    - series: $R_T = R_1 + R_2 + ... + R_n$ and
    - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$
- compare power transfers in series and parallel circuits

Key knowledge units

Equivalent resistance in parallel circuits	1.2.6.4
Parallel circuit analysis	1.2.9.2

Formulas for this lesson

Previous lessons		New formulas
4A	$P = VI$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$ equivalent parallel resistance
4B	$V = IR$	

Definitions for this lesson

node a point in a circuit where multiple components are connected together

parallel circuit an electric circuit that has only parallel connections

parallel connection an arrangement where multiple components connect the same two points so there are multiple alternative pathways for current to flow

Equivalent resistance in parallel circuits 1.2.6.4

OVERVIEW

A parallel circuit contains components that are all connected to the same points, providing multiple pathways for current to flow. The equivalent resistance of parallel components decreases as more parallel components are added to a circuit.

THEORY DETAILS

Parallel circuits

Components in parallel are connected with common nodes to form multiple pathways for current to flow. A node is a point at which two or more components are joined together. Each path between the nodes is called an ‘arm’. When all the components in a circuit are connected in parallel, it is called a parallel circuit. Parallel circuits differ from series circuits in that there is more than one path for current to flow. Figure 1 shows two examples of parallel circuits and their multiple arms.

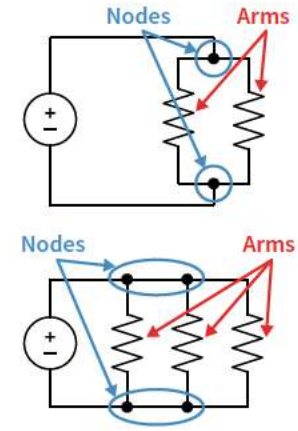


Figure 1 Two parallel circuits with nodes and arms highlighted

Equivalent resistance

To analyse parallel circuits, it is important that we can find the equivalent resistance, R_T, of multiple parallel resistors.

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

R_T = equivalent resistance (Ω), R_n = individual resistance of component n (Ω)

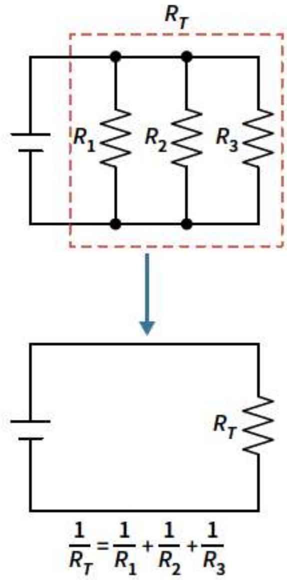


Figure 2 Replacing several parallel resistors with one series resistor of equivalent resistance

The equivalent resistance for components that are connected in parallel represents the resistance of a single pathway that would have the same effect (causing the same amount of current to flow) as the parallel components. This is shown in Figure 2.

The equation for equivalent resistance in a parallel circuit shows us that the equivalent resistance will decrease as more components are added in parallel.

- By adding more components, we are creating additional paths for charge carriers to flow through, hence making it easier for current to flow through the circuit.
- This is similar to parallel water pipes. The more pipes there are connecting two points, the easier it is for water to flow since there is more space to flow through.

Parallel circuit analysis 1.2.9.2

OVERVIEW

Parallel circuits behave very differently to series circuits. We will use Ohm's law to determine the relationship between the current, voltage and power for individual arms within a parallel circuit as well as around the whole parallel circuit.

THEORY DETAILS

Voltage in parallel circuits

In parallel circuits:

- The voltage drop across all parallel arms is the same, and is equal to the supply voltage V_T.
- The resistance of a parallel arm does not affect the voltage drop across that arm.
- Connecting two equal sources in parallel does not affect the total voltage provided.
  - Some electric devices such as toys and laptop batteries connect multiple cells (of the same voltage) in parallel to increase how long the cells last.

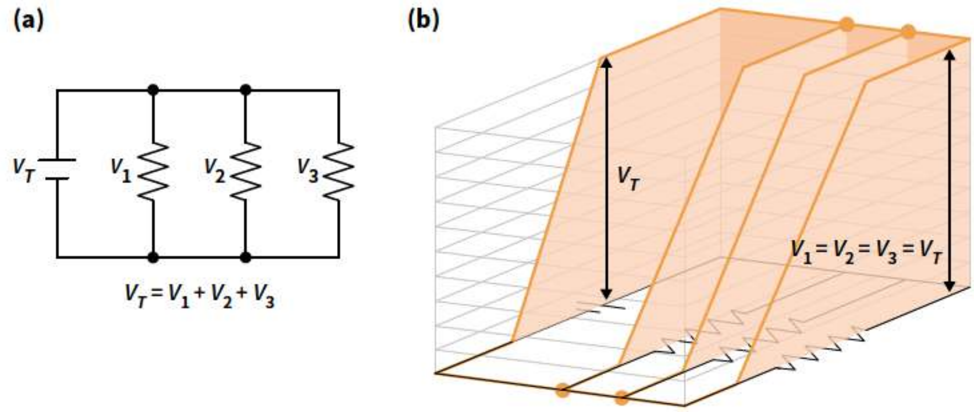


Figure 3 **(a)** A parallel circuit and **(b)** the changes in voltage around the circuit. The total voltage drop across each arm is equal.

Current in parallel circuits

Like in series circuits, the total current provided to a parallel circuit by its source is given by Ohm's law: $I_T = \frac{V_T}{R_T}$. We can see that the total current in a parallel circuit will increase with a greater supplied voltage and decrease with a greater equivalent resistance.

However, in a parallel circuit there are multiple paths for the current to flow, and so the current is split between each arm. The total current must always be equal to the sum of the currents through each arm.

$$I_T = I_1 + I_2 + \ldots + I_n$$

This is a result of electric charge not being able to build up at any point in a circuit, and can be visualised by comparing the current into and out of a node. This is similar to the flow of water at a junction of parallel pipes. The total water entering a junction must equal the total water leaving the junction.

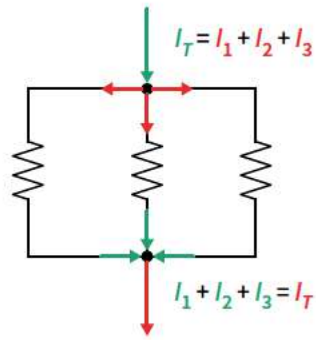


Figure 4 The current flowing into a node (green) is always equal to the current flowing out of a node (red).

The current through any arm in a parallel circuit can be found by applying Ohm's law to that particular arm: $I_n = \frac{V_T}{R_n}$. Since the voltage drop across each resistive component is the same, the current through each component is inversely proportional to its resistance.

$$I_n \propto \frac{1}{R_n}$$

This means that in a parallel circuit, there will be a greater current passing through the arms with lower resistance.

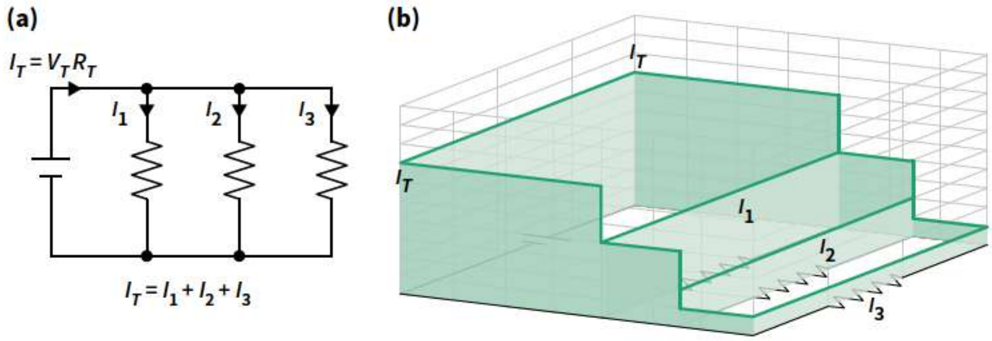


Figure 5 **(a)** A parallel circuit and **(b)** the associated current around the circuit

We can use our formulas relating total and individual currents to reveal the parallel equivalent resistance formula. Since $I_T = \frac{V_T}{R_T}$ and $I_T = I_1 + I_2 + \ldots I_n$, we can say $\frac{V_T}{R_T} = I_1 + I_2 + \ldots I_n$.

We also know $I_n = \frac{V_T}{R_n}$, so we can say $\frac{V_T}{R_T} = \frac{V_T}{R_1} + \frac{V_T}{R_2} + \ldots + \frac{V_T}{R_n}$.

If we cancel V_T from both sides of this equation, we establish the formula for equivalent resistance in parallel circuits: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$.

USEFUL TIP

When you calculate the currents through individual arms of a parallel circuit, make sure that each current:

- is smaller than the total current, and
- follows the inversely proportional relationship between current and resistance.

Power in parallel circuits

In parallel circuits, the total power delivered by a source is equal to the total power used by the load.

$$P_T = V_T I_T = V_T I_1 + V_T I_2 + \ldots + V_T I_n$$

When determining the power delivered or used by a single arm, the correct current value for that arm must be used in the power equation.

- For a source, the current used to calculate power is the total current.
- For an individual load arm, the current used to calculate power is the current through that arm.

When we increase the equivalent resistance in a parallel circuit, we decrease the total current through the circuit as the supplied voltage remains constant. Therefore, increasing the resistance of existing components decreases the power delivered to and used by a circuit.

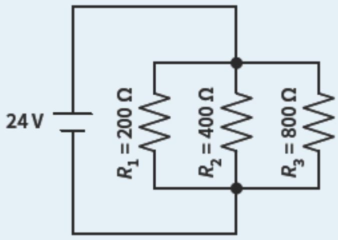
- In series circuits, higher resistance components use more power than lower resistance components. But in parallel circuits, lower resistance components use more power than higher resistance components since they have a greater current.

However, adding more components in parallel will decrease the equivalent resistance and thus increase the total current and total power consumption.

- This is opposite to how adding components affects series circuits, and it is part of the reason that parallel circuits are used in applications like household wiring.
- Adding more components does not affect the power consumption of each individual component.

Worked example 1

An ideal cell is delivering power to a parallel circuit containing three resistors.



a Determine the equivalent resistance of the circuit.

b What is the current through the cell?

c What is the current through R_2?

d What is the power being dissipated by the resistor R_3?

Working	Process of thinking
a $\frac{1}{R_T}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$	Use the formula for the reciprocal of equivalent resistance: $R_1 = 200\ \Omega$, $R_2 = 400\ \Omega$, $R_3 = 800\ \Omega$
$\frac{1}{R_T}=\frac{1}{200}+\frac{1}{400}+\frac{1}{800}=\frac{7}{800}$	
$R_T=\frac{800}{7}=114.3=114\ \Omega$	Invert the result to find the equivalent resistance. To invert a number on your calculator, raise it to the power of −1.
b $V_T = I_T R_T \therefore 24 = I_T \times 114.3$ $I_T = 0.21\ \text{A}$	Use Ohm's law with the source voltage and the equivalent resistance: $V_T = 24\ \text{V}$, $R_T = 114.3\ \Omega$
c $V_2 = I_2 R_2$ $24 = I_2 \times 400$ $I = 0.060\ \text{A}$	Use Ohm's law on R_2 to determine current $V_2 = 24\ \text{V}$, $R_2 = 400\ \Omega$
d $V_3 = I_3 R_3$ $24 = I_3 \times 800$ $I_3 = 0.030\ \text{A}$	Use Ohm's law on R_3 to determine the current $V_3 = 24\ \text{V}$, $R_3 = 800\ \Omega$
$P_3 = V_3 I_3 = 24 \times 0.030$ $P = 0.72\ \text{W}$	Use the voltage drop across R_3 and the current through R_3 to determine the power dissipated by R_3.

Theory summary

- Components in **parallel** are connected side by side with a common node at each end.
- The **equivalent resistance** of resistors in parallel is given by:
  - $\frac{1}{R_T}=\frac{1}{R_1}+\frac{1}{R_2}+\ldots+\frac{1}{R_n}$
- The **voltage** drop over parallel arms is always equal.
- The **current** splits through each arm of a parallel circuit and it is inversely proportional to their resistances.
  - Lower resistance arms will carry a larger current.
  - $I_n \propto \frac{1}{R_n}$
  - At a node, the incoming current is always equal to the outgoing current.
- The **power** used by parallel circuits increases as more arms are added or when resistance is lowered.

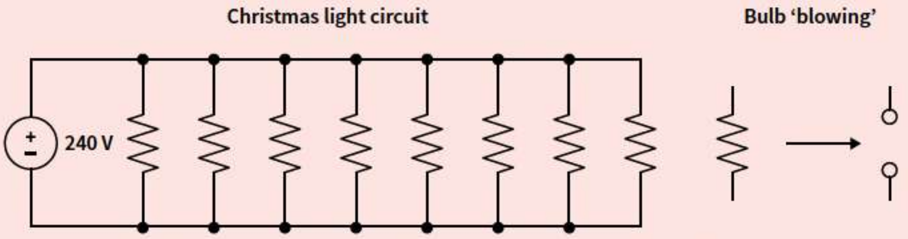
KEEN TO INVESTIGATE?

PhET 'Circuit Construction Kit' simulation
phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab

YouTube video:
The Engineering Mindset – DC parallel circuits explained
youtu.be/5uyJezQNSHw

CONCEPT DISCUSSION QUESTION

A set of Christmas lights are all connected in parallel to a 240 V ideal DC source as shown. When a light 'blows', the electrical connection inside the bulb is broken and the device becomes a gap in the circuit.



Discuss whether the remaining bulbs will stay on if one of the bulbs blows. How would the power consumption of each remaining bulb change when this bulb blows?

Answers on page 505

Hints
Are there still any completed circuits after a bulb blows?
Does a change in total equivalent resistance change the power consumption of existing components?

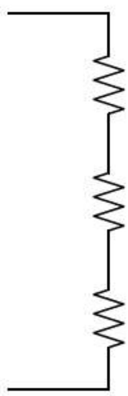
4D Questions

THEORY REVIEW QUESTIONS

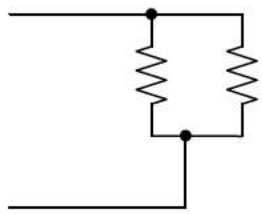
Question 1

Which of the following sets of components are connected only in parallel? *(Select all that apply)*

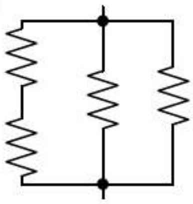
I



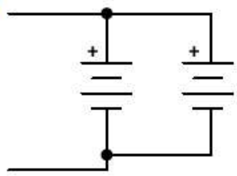
II



III

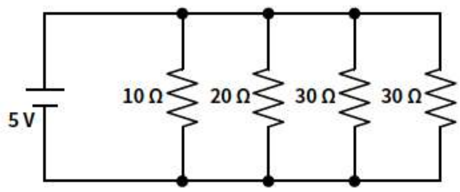


IV



Question 2

Which of the following statements about this circuit is incorrect?



A The sum of the currents through each resistor is equal to the current through the cell.

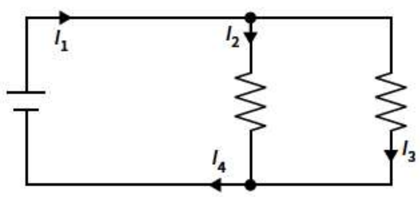
B The voltage drop across both 30 Ω resistors is equal.

C The current through the 10 Ω resistor would be larger than the current through the 20 Ω resistor.

D The voltage drop across each resistor is proportional to their resistance.

Question 3

Which of the following equations is true for this circuit?



A $I_1 = I_2 = I_3 = I_4$

B $I_1 + I_2 = I_3 + I_4$

C $I_1 = I_2 + I_3 = I_4$

D $I_1 - (I_2 + I_3) = I_4$

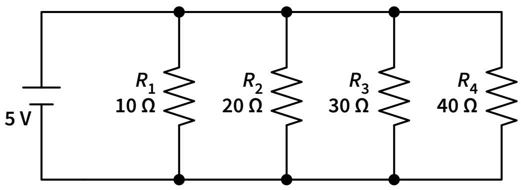
Question 4

Fill in the blanks below to complete the paragraph about parallel circuits.

In parallel circuits, multiple components are connected __________ (end to end/to the same node). When more resistive components are added to a parallel circuit powered by an ideal source, the power consumption of the circuit __________ (decreases/increases/stays the same), while the power consumption of each original resistive component __________ (decreases/increases/stays the same).

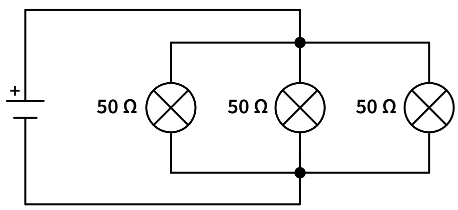
Question 5

List the four resistors below in an increasing order of the power they consume.



Question 6

Which of the following would **not** happen to the circuit shown if one bulb were removed? When removed, the bulb is replaced by a gap in the circuit.



A The power consumption of each remaining bulb would not change.

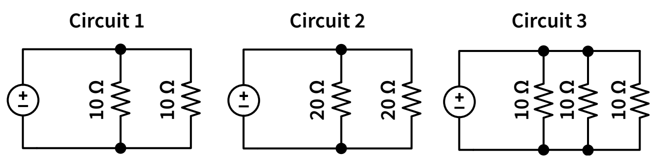
B The power consumption of the circuit would decrease.

C No current would flow through the circuit since there is a gap.

D The voltage across each bulb would remain the same.

Question 7

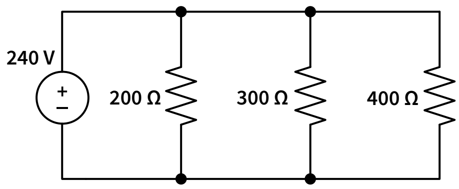
Rank the three circuits below from the lowest equivalent resistance to the highest equivalent resistance.



DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (4 MARKS)

A 240 V DC power source is being used to run a set of appliances wired in parallel. Assume each appliance can be modelled as a resistor.



Prompts

a What is the voltage across the 300 Ω resistor?

A 240 V

B 120 V

C 80 V

D 60 V

b Which of the following equations could be used to find the total current provided by the source?

A $240 = I_T \times 300$

B $80 = I_T \times 900$

C $240 = I_T \times R_T$

D $80 = I_T \times R_T$

c Which of the following equations could be used to find the current through the 300 Ω resistor?

A $240 = I_{300\ \Omega} \times 300$

B $80 = I_{300\ \Omega} \times 900$

C $240 = I_{300\ \Omega} \times R_T$

D $80 = I_{300\ \Omega} \times R_T$

Question

d By calculating both power values, determine what fraction of the total power delivered by the source is consumed by the 300 Ω resistor. (4 MARKS)

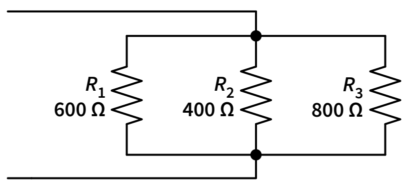
EXAM-STYLE QUESTIONS

This lesson

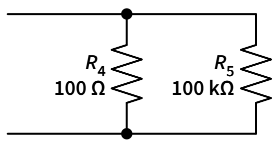
Question 9 (2 MARKS)

Determine the equivalent resistance of the following parallel resistors.

a

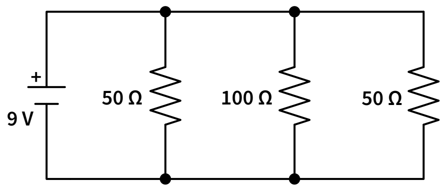


b



Question 10 (4 MARKS)

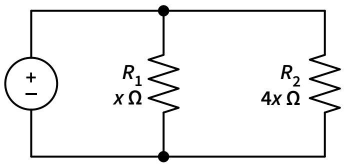
a Determine the total current provided to this parallel circuit by the ideal cell. (2 MARKS)



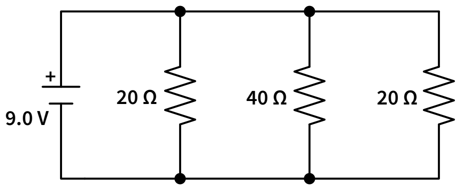
b Determine the current passing through the 100 Ω resistor. (2 MARKS)

Question 11 (2 MARKS)

The total current provided to this parallel circuit by the ideal DC source is 5.0 A. Calculate the current passing through R_2.



Question 12 (5 MARKS)



a Determine the total power dissipated by this parallel circuit. (3 MARKS)

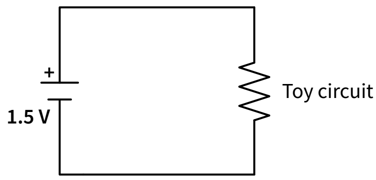
b Determine the power dissipated by the two 20 Ω resistors. (2 MARKS)

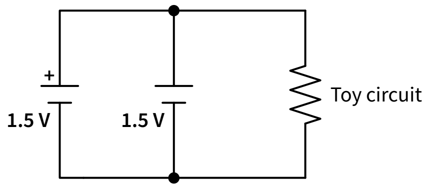
Question 13 (2 MARKS)

Joanne is comparing different sets of decorative lights and wants to choose the lights with the lower power consumption. The two sets of lights contain different numbers of identical bulbs which have the same electrical characteristics and are connected in parallel. Explain whether Joanne should choose the set with more or fewer lights.

Question 14 (5 MARKS)

The circuit for an electronic toy can be driven by either a single 1.5 V cell or two 1.5 V cells in parallel, as shown. With reference to Ohm's law, compare the voltage and current provided by the cell/cells to the circuit in each setup.





Question 15 (1 MARK)

What would be the effect on power consumption if infinitely many resistors were added to an ideal source in parallel?

Question 16 (3 MARKS)

An engineer is tasked with constructing a radio tuning circuit and requires a 200 Ω resistor. However, the only resistors available are one each of a 100 Ω, a 400 Ω, a 600 Ω, a 1000 Ω, and a 1200 Ω resistor. Draw a parallel combination of resistors that the engineer can use to create a 200 Ω resistor.

Previous lessons

Question 17 (1 MARK)

What is the driving factor influencing the formation of energy flows at the Earth's surface?

Question 18 (3 MARKS)

a Determine the resistance of a bulb that draws a current of 10 A when a potential difference of 240 V is applied. (1 MARK)

b If the bulb filament is 2.0 cm long and has a cross-sectional area of 1.0 mm^2, determine the resistivity of the filament. (2 MARKS)

Key science skills

Question 19 (3 MARKS)

Rahj conducts an investigation where he measures the total current supplied by a voltage source to a parallel circuit as different numbers of 1 kΩ resistors are connected. Identify the independent variable, the dependent variable, and a controlled variable in this experiment.

4E COMBINING SERIES AND PARALLEL CIRCUITS

As we encounter more complex electrical circuits that do more interesting things, they become harder to analyse. In this lesson, we will introduce complex circuits that contain combinations of series and parallel connections. By applying our prior knowledge of equivalent resistance and circuit behaviour, we will learn to analyse and solve these combination circuits.

4A What is electricity?	4B Resistance and Ohm's law	4C Series circuits	4D Parallel circuits	4E Combining series and parallel circuits

Study design dot point

- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers

Key knowledge unit

Combination circuits	1.2.7.1

Formulas for this lesson

Previous lessons		New formulas
4A	$P = VI$	No new formulas for this lesson
4B	$V = IR$	
4C	$R_T = R_1 + R_2 + \ldots + R_n$	
4D	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$	

Combination circuits 1.2.7.1

OVERVIEW

Combination circuits contain both series and parallel connections. To solve problems with combination circuits, we have to apply equivalent resistance formulas and Ohm's law at multiple stages.

THEORY DETAILS

Many circuits contain a combination of series and parallel connections. These are called combination circuits. Combination circuits are more difficult to analyse than those having only one connection type, since we have to use multiple equivalent resistance equations and often apply Ohm's law multiple times to find the desired quantities.

Analysing combination circuits

Many combination circuit questions require finding the total equivalent resistance of a circuit. To do this:

- Find the equivalent resistance of small groups of components connected only in series or parallel.
- Redraw the circuit with each of these groups drawn as a single equivalent resistor.
- Repeat these steps until the total equivalent resistance is found.

Ohm's law and the electric power equation can be used with this total equivalent resistance to find the total current, voltage, and power for the circuit.

When writing out working for circuit analysis questions, it can be efficient to use the parallel symbol || between resistors to represent an equivalent parallel resistance. For example, writing $R_1 || R_2$ is equivalent to writing $\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$.

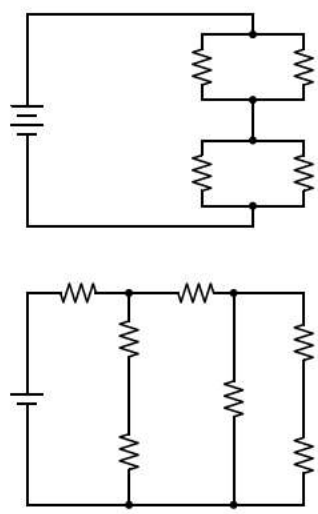


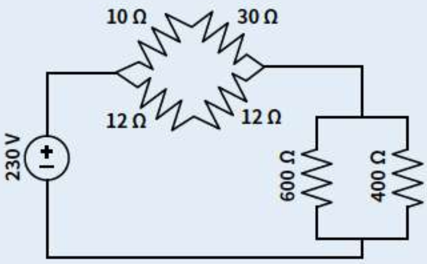
Figure 1 Two combination circuits. Combination circuits can feature complex structures like series connections of parallel elements and series connections within parallel arms.

USEFUL TIP

Some combination circuits are displayed with unfamiliar style, like in Worked example 1. It can be helpful to redraw part or all of the circuit to make it look more familiar.

Worked example 1

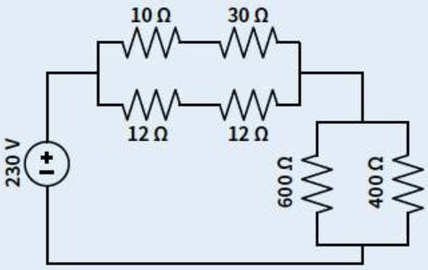
Determine the total power consumed by this electric heater circuit.



Working

Process of thinking

Redraw the circuit in a more familiar shape.

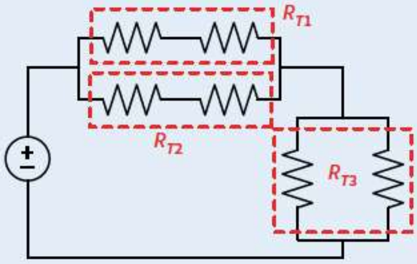


$R_{T1} = 10 + 30 = 40\ \Omega$

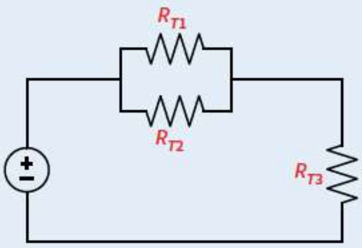
$R_{T2} = 12 + 12 = 24\ \Omega$

$R_{T3} = 600||400 = \left(\frac{1}{600} + \frac{1}{400}\right)^{-1} = 240\ \Omega$

Calculate the equivalent resistance of groups with only one connection type.

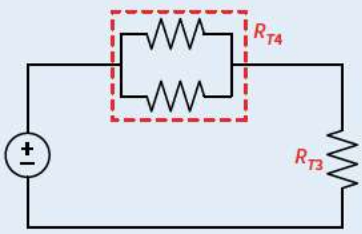


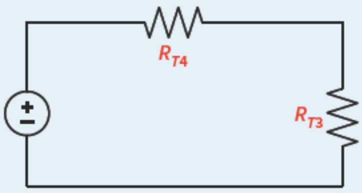
Redraw the circuit with equivalent resistors.



$R_{T4} = R_{T1}||R_{T2} = \left(\frac{1}{40} + \frac{1}{24}\right)^{-1} = 15\ \Omega$

Calculate the equivalent resistance of groups with only one connection type.

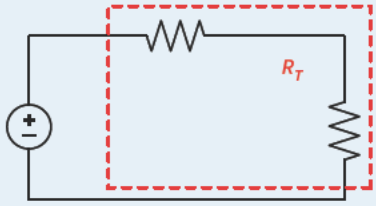




Redraw the circuit with equivalent resistors.

$R_T = R_{T4} + R_{T3} = 15 + 240 = 255\ \Omega$

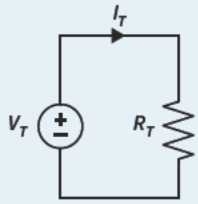
Calculate equivalent resistance of the final group to find total equivalent resistance.



$I_T = \frac{V_T}{R_T} = \frac{230}{255} = 0.902\ \text{A}$

$P_T = V_T I_T = 230 \times 0.902 = 207\ \text{W}$

Use Ohm's law to find the total current, and the electric power equation to find the total power consumed.

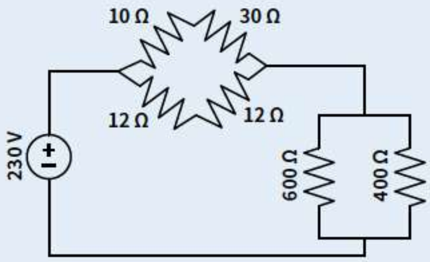


Combination circuit analysis can also involve finding the **current**, **voltage drop**, and/or **power** for particular components within the circuit. To achieve this:

- If not provided, find the total current and voltage provided to the circuit using Ohm's law and the total equivalent resistance.
- Split the equivalent resistance back into smaller groups of components and use Ohm's law to calculate the current and/or voltage for these components.
- Continue to work backwards, splitting component groups until you can use Ohm's law to determine the current and/or voltage for the specified component.
- Use the power equation with the current and voltage drop for the specific component if required.

Worked example 2

Determine the current through the 400 Ω resistor in the electric heater circuit from Worked example 1.



Working

$I_T = 0.902$ A

$I_{group\ 2} = I_T = 0.902$ A

$R_{group\ 2} = 600||400 = \left(\frac{1}{600} + \frac{1}{400}\right)^{-1} = 240\ \Omega$

$V_{400\ \Omega} = V_{group\ 2} = I_{group\ 2} \times R_{group\ 2}$

$V_{400\ \Omega} = 0.902 \times 240 = 216$ V

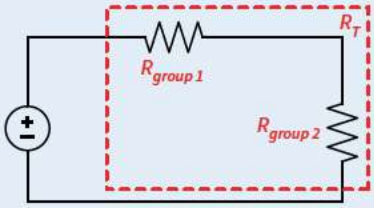
$I_{400\ \Omega} = \frac{V_{400\ \Omega}}{R_{400\ \Omega}} = \frac{216}{400}$

$I_{400\ \Omega} = 0.541$ A

Process of thinking

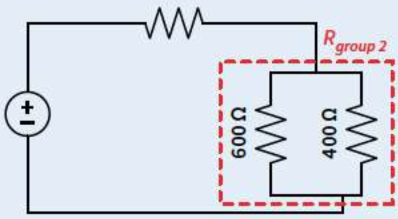
Use $I_T = 0.902$ A, which was the total current provided to the circuit as found in Worked example 1.

Split the equivalent resistance R_T into two groups, corresponding to each set of parallel components.



Since these groups are in series, the current through both groups is equal to the total current.

Split group 2 into its original components.



Calculate the equivalent resistance of this group.

Use Ohm's law to find the voltage across group 2. Since the components are in parallel, this is also the voltage across the 400 Ω resistor.

Use Ohm's law to find the current through the 400 Ω resistor.

Theory summary

- Circuits often have components in a combination of series and parallel connections.
- To analyse combination circuits, we have to calculate equivalent resistances at multiple levels.
  - We start with small sections of the circuit which only contain one type of connection, and then 'replace' those sections with a single equivalent resistor.
  - A total equivalent resistance can be found to use $V_T = I_T R_T$.
  - Solving for specific values requires working backwards from total values.

KEEN TO INVESTIGATE?

oPhysics 'Electric Circuit' simulation
ophysics.com/em4a.html

PhET 'Circuit Construction Kit' simulation
phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab

CONCEPT DISCUSSION QUESTION

When we measure the voltage across a component, a voltmeter is connected in parallel with that component. However, a voltmeter is a resistive component, which we would expect to affect the operation of the circuit.

Discuss the requirement for the voltmeter resistance in order for its measurement to accurately represent the component voltage if the voltmeter were not present.

Answers on page 505

Hints

What is the equivalent resistance of a parallel connection when one resistor has a much greater resistance than the other?

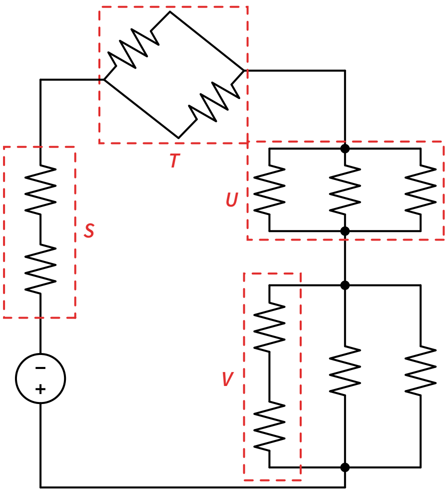
Would the voltmeter need to be the resistor with a much greater or a much smaller resistance than the other parallel component?

4E Questions

THEORY REVIEW QUESTIONS

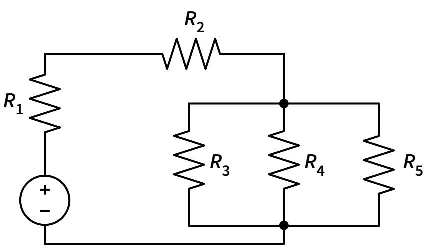
Question 1

Identify the types of connections (**series or parallel**) for each labelled group of components *S*, *T*, *U*, and *V* in this combination circuit.



Question 2

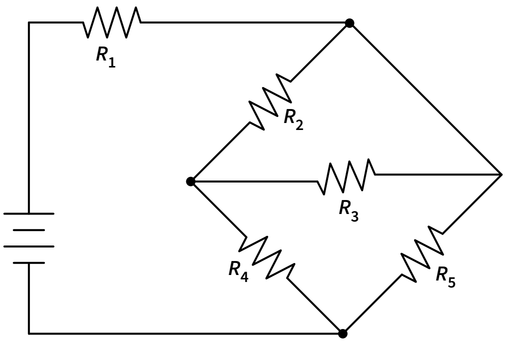
Simone has been asked to find the current passing through R_4. Number the actions below to create a step-by-step process for Simone to solve this problem.



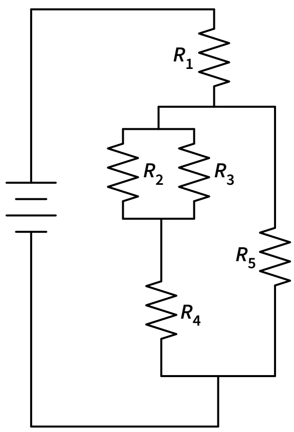
Step no.	Action
	Find total equivalent resistance of the circuit
	Find the equivalent resistance of the parallel resistors
	Find the current passing through R_4 using Ohm's law or $I_n \propto \frac{1}{R_n}$
	Find the total current using Ohm's law

Question 3

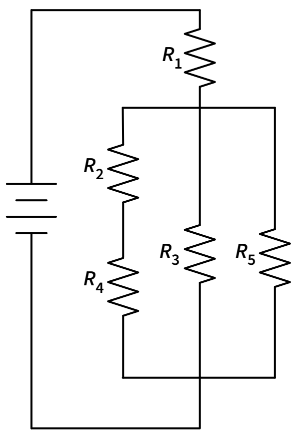
Which of the following options is an equivalent circuit diagram to this combination circuit?



A



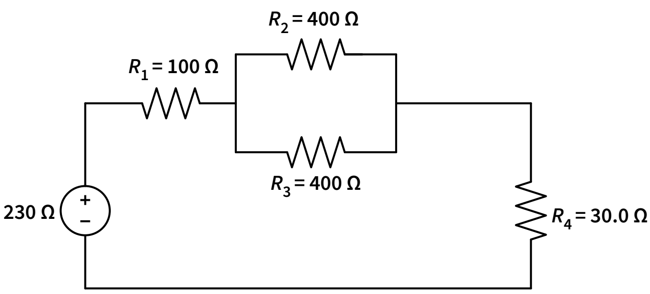
B



DECONSTRUCTED EXAM-STYLE QUESTION

Question 4 (4 MARKS)

This electric circuit represents the internal circuitry of an appliance.



Prompts

a Which of the following is closest to the equivalent resistance for the group of components containing R_2 and R_3 only?

A 100 Ω

B 200 Ω

C 400 Ω

D 800 Ω

b Which of the following is closest to the total equivalent resistance of the circuit?

A 20.0 Ω

B 230 Ω

C 330 Ω

D 930 Ω

c Which of the following statements about the appliance circuit is **incorrect**?

A The current through R_4 is equal to $\frac{I_T}{R_4}$

B The current through R_4 is equal to I_T

C The voltage across R_4 is equal to $\frac{R_4}{R_T} \times V_T$

D The voltage across R_4 is equal to $I_T \times R_4$

Question

d How much power is consumed by R_4? (4 MARKS)

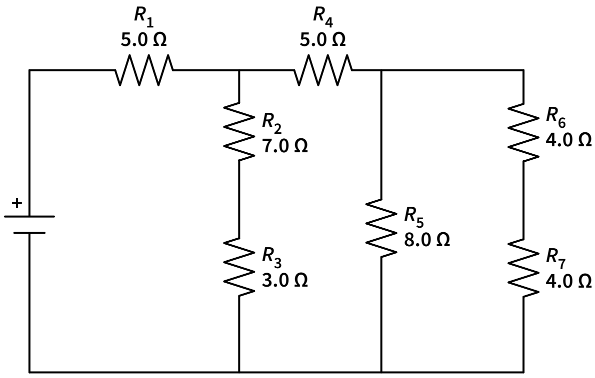
EXAM-STYLE QUESTIONS

This lesson

Question 5 (6 MARKS)

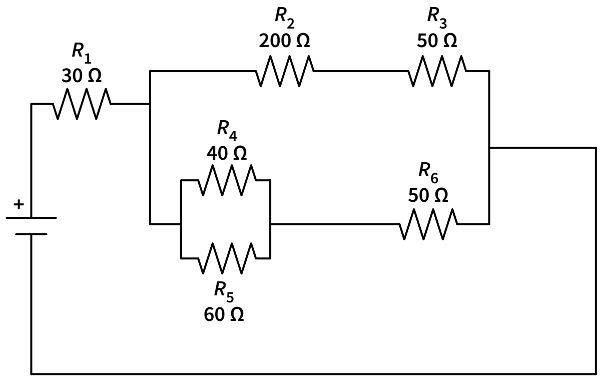
Determine the equivalent resistance of each combination circuit.

a



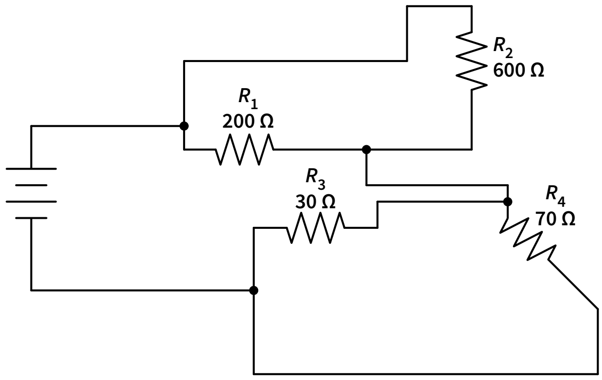
(2 MARKS)

b



(2 MARKS)

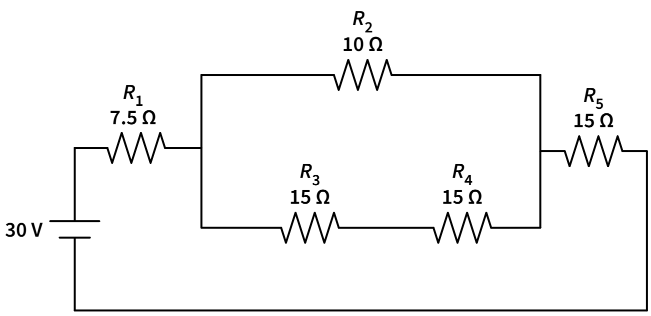
c



(2 MARKS)

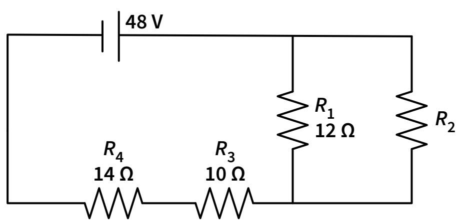
Question 6 (4 MARKS)

Determine the voltage drop across R_1 and R_4 in this combination circuit.



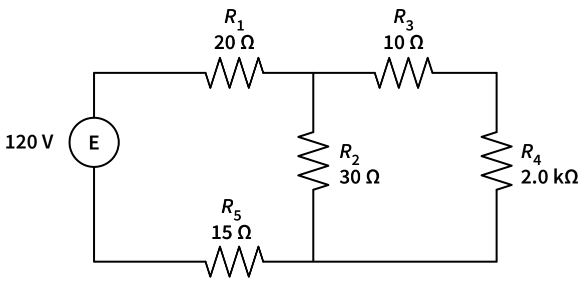
Question 7 (5 MARKS)

1.0 A of current flows through R_1 in this combination circuit. Determine the resistance of R_2.



Question 8 (5 MARKS)

Which of the resistors in this combination circuit would consume the most power? Show your working.



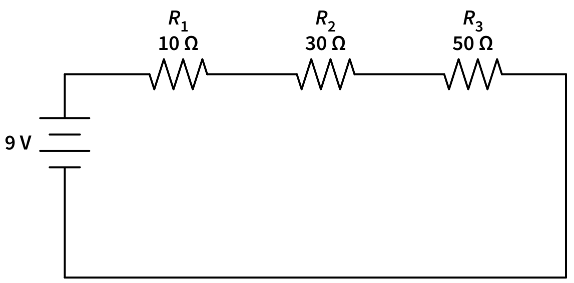
Previous lessons

Question 9 (2 MARKS)

During which Southern Hemisphere season does Australia receive the greatest intensity of solar radiation? Explain why this is the case. Ignore the effects of weather.

Question 10 (2 MARKS)

Determine the total current provided by the source in this series circuit.



Key science skills

Question 11 (3 MARKS)

Joanne has performed two experiments to determine the total current provided to a combination circuit. She records the following results:

	I_T (mA)				
Experiment 1	5.5	5.4	5.6	5.6	5.6
Experiment 2	5.8	5.1	5.9	5.9	5.5

The true value of I_T is known to be 5.5 mA.

Determine which experiment produced the more precise results, and which experiment produced the more accurate results. Explain your answer.

CHAPTER 4 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Which of the following correctly describes how electrical quantities are affected by two elements with different resistances in series or parallel?

	Series	Parallel
A	power is split between the two	power is equal
B	current is equal	potential difference is equal
C	current is equal	potential difference is split between the two
D	potential difference is equal	current is split between the two

Question 2

The magnitude of the charge of an electron is 1.60×10^{-19} C. Using this information, the number of electrons flowing every second through a 45 W toaster that is connected to a 240 V power supply would be closest to

A 1.2×10^{17}

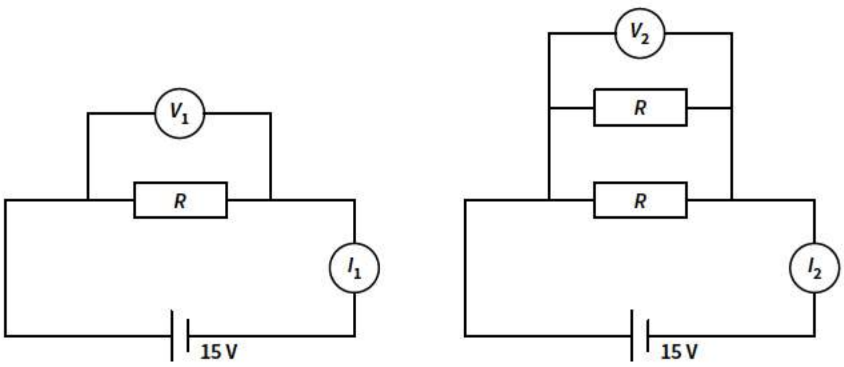
B 1.2×10^{18}

C 3.3×10^{19}

D 2.8×10^{20}

Question 3

The following diagram depicts two simple circuits. In both circuits, *R* represents a resistor of identical resistance.



V_1 and V_2 are readings from ideal voltmeters. I_1 and I_2 are readings from ideal ammeters. Which one of the following statements is true?

A $V_2 = V_1$ and $I_2 > I_1$

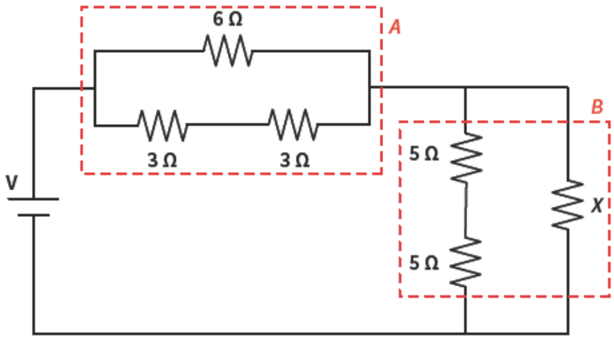
B $V_2 = V_1$ and $I_2 < I_1$

C $V_2 > V_1$ and $I_2 > I_1$

D $V_2 > V_1$ and $I_2 < I_1$

Use the following information to answer Questions 4 and 5.

The provided diagram shows two sets of parallel resistors *A* and *B* in a combination circuit. *X* is a resistor with an unknown resistance.



Question 4

Which one of the following statements is true?

A The equivalent resistance of *A* is 6 Ω.

B The equivalent resistance of *A* is 12 Ω.

C The equivalent resistance of *B* cannot exceed 10 Ω.

D The equivalent resistance of *B* must be above 10 Ω.

Question 5

If the circuit has a total equivalent resistance of 11 Ω, which of the following is closest to the resistance of *X*?

A 5 Ω

B 10 Ω

C 20 Ω

D 40 Ω

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

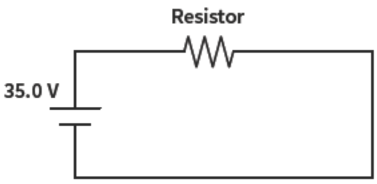
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (7 MARKS)

A new solid, cylindrical resistor with a length of 1.20 cm is being tested by manufacturers. It has a resistance of 8.00×10^4 Ω, and is made from a material with a resistivity of 640 Ω m.

a Calculate the radius of this resistor in cm. (2 MARKS)

Thermal management is an important design challenge for electrical components. The manufacturers want to know how the resistor's temperature changes during normal use. They place the resistor in the circuit shown in the provided diagram. The resistor has a mass of 5 g and its material has a specific heat capacity of 753 J kg^{-1} K^{-1}.

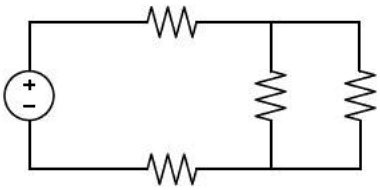


b Show that the power dissipated by the resistor is equal to 1.53×10^{-2} W. (2 MARKS)

c Calculate the change in temperature of the resistor over a period of 600 seconds. Assume that no thermal energy leaves the resistor. (3 MARKS)

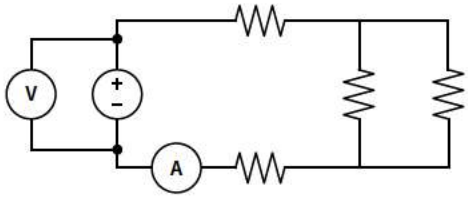
Question 7 (3 MARKS)

Students are attempting to determine the power usage of a circuit with unknown electrical quantities.

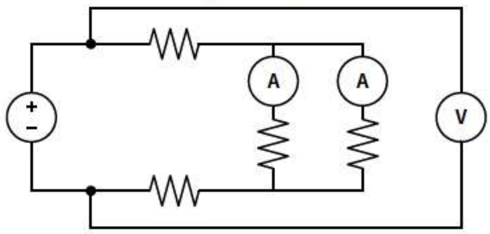


Erin believes that they can determine the power usage of the circuit by placing a voltmeter and ammeter as shown. Jack disagrees. He says that in order to know the total power they need to check the voltage and current across the entire circuit, and proposes a different circuit arrangement.

Erin's setup



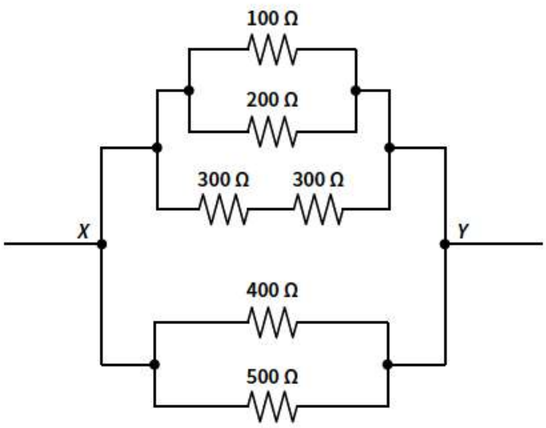
Jack's setup



Which student's setup will allow them to determine the total power usage of the circuit? Explain your answer.

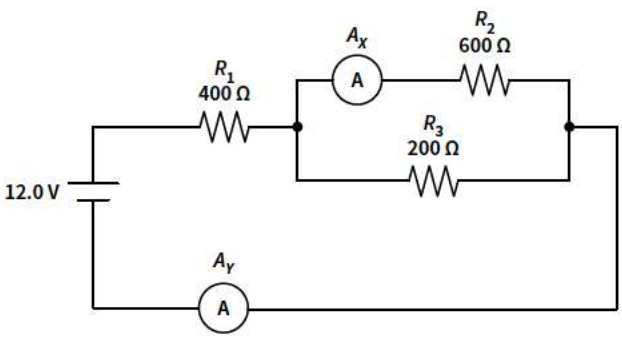
Question 8 (4 MARKS)

Calculate the equivalent resistance between X and Y for the following combination circuit.



Question 9 (11 MARKS)

Consider the following circuit which shows three resistors wired to two ammeters and a 12.0 V power source.

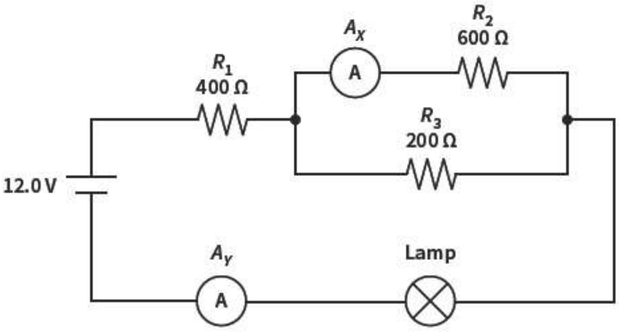


a Calculate the ratio of the current through A_X to the current through A_Y. (2 MARKS)

b Calculate the potential difference across R_1. (3 MARKS)

c Calculate the power dissipated by R_3. (3 MARKS)

d A lamp is inserted into the circuit in series with A_Y, which now reads 15 mA. Calculate the resistance of the lamp. (3 MARKS)



UNIT 1 AOS 2, CHAPTER 5

Applied electricity

05

Key knowledge

- apply the kilowatt-hour (kW h) as a unit of energy
- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers
- model household (AC) electrical systems as simple direct current (DC) circuits
- explain why the circuits in homes are mostly parallel circuits
- investigate and apply theoretically and practically concepts of current, resistance, potential difference (voltage drop) and power to the operation of electronic circuits comprising resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers (quantitative analysis restricted to use of $I = \frac{V}{R}$ and $P = VI$)
- describe energy transfers and transformations with reference to transducers
- model household electricity connections as a simple circuit comprising fuses, switches, circuit breakers, loads and earth
- compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs)
- describe the causes, effects and treatment of electric shock in homes and identify the approximate danger thresholds for current and duration.

5A APPLICATIONS OF ELECTRIC CIRCUITS

Electric circuits are used all over the world to perform all kinds of jobs, from cooking food to flying planes. This lesson will explore the uses of voltage dividers, analyse non-ideal component behaviour, and introduce diodes and advanced resistors to help understand how complex circuits work.

5A Applications of electric circuits	5B Household electricity	5C Electrical safety

Study design dot points

- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers
- investigate and apply theoretically and practically concepts of current, resistance, potential difference (voltage drop) and power to the operation of electronic circuits comprising resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers (quantitative analysis restricted to use of $I = \frac{V}{R}$ and $P = VI$)
- describe energy transfers and transformations with reference to transducers

Key knowledge units

Voltage dividers	1.2.7.2
Behaviour of real electrical components	1.2.11.1
Diodes and light-emitting diodes	1.2.11.2
Advanced resistors	1.2.11.3 & 1.2.13.1

Formulas for this lesson

Previous lessons		New formulas
4A	$P = VI$	$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$ voltage divider equation
4B	$V = IR$	

Definitions for this lesson

diode a semiconductor device which limits current flow to one direction

internal resistance the inherent resistance associated with an electric power source

light-dependent resistor a variable resistor that decreases resistance as the intensity of light hitting its sensitive surface increases

light-emitting diode a diode that emits light when a potential difference is applied

potentiometer a variable resistor that changes resistance depending on the manual control of a sliding contact

thermistor a variable resistor that changes resistance with temperature

transducer a component or device that transforms energy between different forms

voltage divider a resistive circuit that outputs a voltage smaller than its input voltage

Voltage dividers 1.2.7.2

OVERVIEW

Voltage dividers use the ratio of resistances between two resistors to output a specific voltage that is smaller than the input voltage.

THEORY DETAILS

Many complex circuits require different voltages to operate their various components. As such, it is often required to 'divide' a fixed input voltage into a smaller output voltage. The simplest method to achieve this is to use a voltage divider.

- A voltage divider consists of two resistors in series, with the output defined as the voltage across one of the resistors.
- Since the resistors are in series, the total input voltage is split between the resistors proportional to their resistances.

If we define R_2 as the output resistor:

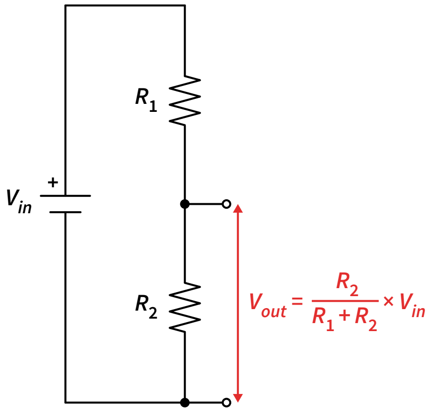


Figure 1 A voltage divider

$$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$$

V_{out} = output voltage (V), R_2 = resistance of output resistor (Ω),
R_1 = resistance of other resistor (Ω), V_{in} = input voltage (V)

The performance of voltage dividers is **heavily affected by the load** that is connected at the output.

- The output resistor R_2 and the connected load R_L form a parallel connection.
- When R_L is significantly larger than R_2, like when a voltmeter is the load, the output voltage is not significantly affected.
- However, if the load resistance is not much greater than R_2, the output voltage will be significantly reduced.

This loading effect is a key limitation of voltage dividers, and the reason that more complex voltage converters are used when a load needs to be powered.

Behaviour of real electrical components 1.2.11.1

OVERVIEW

Real electrical components have non-ideal properties. Light bulbs do not behave as ohmic resistors, and voltage and current sources have an associated internal resistance.

THEORY DETAILS

In Chapter 4, we analysed circuits with ideal sources and mainly ohmic components. However, real components have limitations that make their behaviour non-ideal.

Light bulbs

Light bulbs are often modelled as resistors with a constant resistance, however light bulbs do not behave like this in real circuits.

Incandescent (filament) bulbs produce light through thermal radiation by heating their filament with a current. We learned in Lesson 4B that resistance is dependent on temperature, so when the filament heats up, its resistance increases.

- When a small voltage is applied to an incandescent bulb, a small current flows, so the filament does not heat up significantly and the resistance remains small.
- As the voltage increases, the current increases and the filament heats up more, increasing the resistance.
- Because the resistance is increasing with the applied voltage, the light bulb is a non-ohmic device.

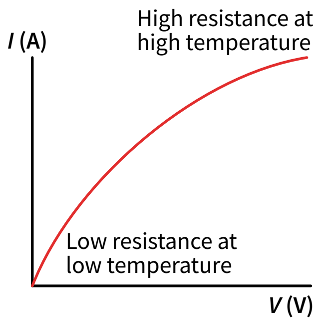


Figure 2 An *I*-*V* graph of an incandescent bulb. As the applied voltage and current increases, the temperature of the filament rises, increasing the resistance of the bulb and limiting the current.

Non-ideal sources

In previous lessons, we analysed circuits containing ideal sources that have no limitations on their outputs. Real sources, however, have an inherent internal resistance that affects the current and output voltage that can be provided to a circuit. The internal resistance is modelled as a resistor R_i in **series** with the source.

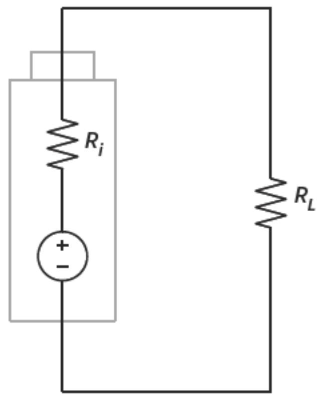


Figure 3 A non-ideal voltage source such as a battery is modelled as an ideal voltage source in series with an internal resistance R_i.

The internal resistance of a source is usually quite small: a 1.5 V AA cell might have an internal resistance between 0.1 Ω and 1 Ω.

The internal resistance can have some significant effects on circuit behaviour:

- The voltage provided to the circuit (the load) is smaller than that of the ideal voltage source.
  - This effect is reduced when the load resistance is much greater than the internal resistance.
- The current provided by the source is reduced, since the internal resistance increases the total equivalent resistance of the circuit. This effect is small when the load resistance is much greater than the internal resistance.
- The source cannot provide unlimited amounts of current: the **maximum current is limited** by the internal resistance.

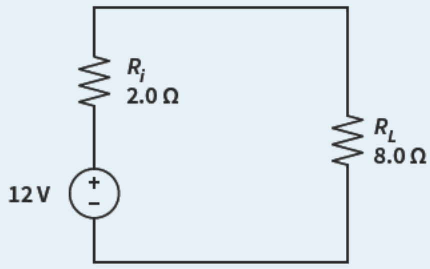
From the effects described above, we can conclude that for our circuit to behave as we desire, we either need to know the internal resistance of the source and consider its effects, or ensure that our load resistance is large enough that the impacts of the internal resistance are negligible.

Worked example 1

A DC voltage source is being used to drive a simple circuit. The source has an internal resistance of 2.0 Ω (R_i).

a Determine the voltage provided to the load resistor R_L.

b Determine the difference between the current provided by the load if there were no internal resistance and the current provided when there is an internal resistance of 2.0 Ω.



Working	Process of thinking
a $V_L = \frac{R_L}{R_i + R_L} \times V_T$ $V_L = \frac{8.0}{2.0 + 8.0} \times 12$ $V_L = 9.6\text{ V}$	Use the voltage divider equation with V_{out} as V_L and V_{in} as V_T.
b Without R_i: $I = \frac{V_T}{R_T} = \frac{12}{8.0} = 1.5\text{ A}$ With R_i: $I = \frac{V_T}{R_i + R_L} = \frac{12}{10.0} = 1.2\text{ A}$ Difference = 1.5 − 1.2 = 0.3 A	Use Ohm's law with the two total resistances and constant supply voltage.

Diodes and light-emitting diodes 1.2.11.2

OVERVIEW

Diodes are semiconductor devices that only allow current to flow in one direction. Light-emitting diodes (LEDs) are a type of diode that produces light under a potential difference.

THEORY DETAILS

Semiconductor materials like silicon can be manipulated (by what is called doping) to either increase or decrease the number of free electrons (which allow conduction of electric currents) they contain. When a positive (fewer free electrons) and a negative (more free electrons) semiconductor are connected to form a p-n junction, a diode is formed.

Due to the physical properties of the semiconductor materials, this junction only allows current to flow in one direction.

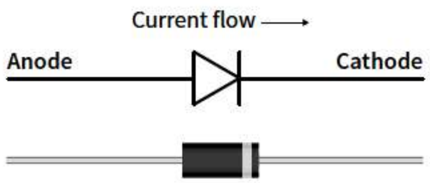


Image: Heavypong/Shutterstock.com

Figure 4 The circuit diagram symbol for a diode and a real diode. The diode allows (conventional) current flow from the anode to the cathode.

The circuit symbol for a diode indicates the direction that current can flow through the diode. Using conventional current (from positive to negative terminals), current can flow from the anode to the cathode of the diode, which is the direction the 'arrow' of the diode symbol is pointing.

- We can think of the line on the cathode side of the diode as a wall stopping current from flowing in the opposite direction.

Light-emitting diodes

A light-emitting diode (LED) is a type of diode specifically designed to emit light when a potential difference is applied. It converts electric potential energy into light when electrons move across the semiconductor junction.

Like a regular diode, current can only flow one way through an LED, so the potential difference applied to the LED must be in the correct direction (higher voltage on the anode side) for the LED to light up, or the LED will not work.

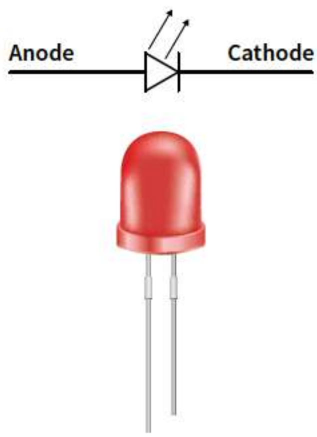


Image: petrroudny43/Shutterstock.com

Figure 5 The circuit diagram symbol for an LED and a real LED. Note that the anode of a real LED will be longer than the cathode so that it can be easily wired in the correct direction.

Using diodes in circuits

Diodes are used in circuits to ensure current only flows in one direction. This can be useful to protect sensitive components from backwards currents when sources are connected the wrong way.

- When analysing a circuit with a diode, start by checking whether any current will flow.
- If current is flowing, use the diode threshold voltage to determine the voltage drop for the rest of the circuit.

When a potential difference is applied to a diode that creates a current flow, there will be a voltage drop across the diode. This is known as the threshold voltage, V_t. We can use the *I-V* graph of a diode to find the threshold voltage.

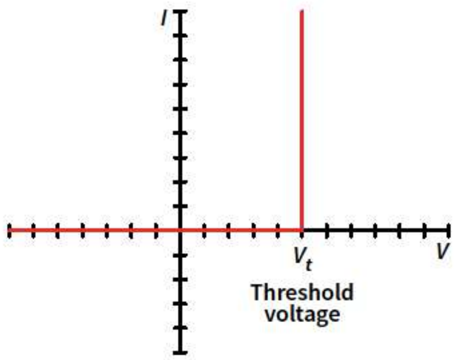


Figure 6 The *I-V* graph of a diode with ideal characteristics. When the threshold voltage V_t is reached a current will flow.

Most diodes have a small threshold voltage of around 0.7 V. Our analysis of diodes will be limited to ideal diodes, where once the threshold voltage is met, unlimited current can flow without affecting the voltage drop across the diode.

LEDs operate much the same as regular diodes in circuits, however they often have a much higher threshold voltage, commonly around 1.5 V – 3 V. One important requirement when designing circuits that use LEDs is to limit the current passing through each LED. Too much current will cause an LED to burn out, so a current-limiting resistor must be placed in series with the LED to prevent failure.

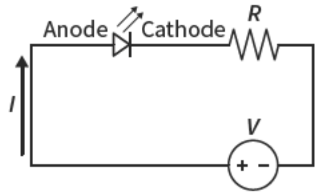
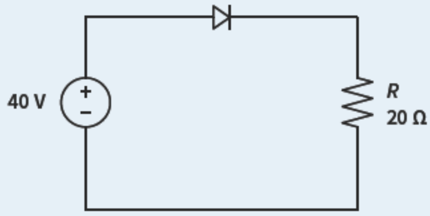


Figure 7 The use of a current-limiting resistor in an LED circuit

Worked example 2

A diode is being used to protect a sensitive circuit from a backwards current when its source is connected the wrong way. The diode has a threshold voltage of 1.1 V and is ideal. Determine the current through the diode when the source is connected as shown.



Working	Process of thinking
	Check that current will flow through the diode: • Voltage is applied from the anode to the cathode • Voltage applied exceeds threshold voltage
$V_R = V_T - V_{diode} = 40 - 1.1$ $V_R = 38.9 \text{ V}$	The voltage supplied to the resistor will be reduced by the diode threshold voltage.
$I_{diode} = I_R = \frac{V_R}{R}$ $I_{diode} = \frac{38.9}{20} = 1.9 \text{ A}$	The current through the diode is equal to the current through the resistor.

Advanced resistors 1.2.11.3 & 1.2.13.1

OVERVIEW

Variable resistors respond to manual control, or inputs like light intensity and temperature, to have a range of resistance values. Circuits that transform energy between different forms are known as transducers.

THEORY DETAILS

Potentiometers

Potentiometers are electrical components that can have their resistance varied by manually moving a rotating or sliding contact. The potentiometer has a fixed length of resistive material, and the position of the contact determines how much of this length is active in the circuit. We know that the length of a resistive material affects the total resistance of a component, so when the contact is moved to increase the length of resistive material being used, the potentiometer's resistance increases.

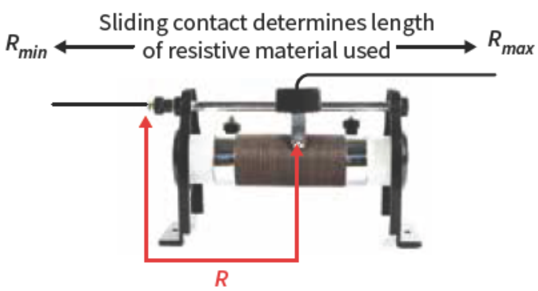


Image: sNike/Shutterstock.com

Figure 8 A potentiometer with a sliding contact. The resistance across the entire device is constant, but changing the slider position alters the length between the start of the potentiometer and the centre contact. The distance between the contacts is proportional to the resistance.

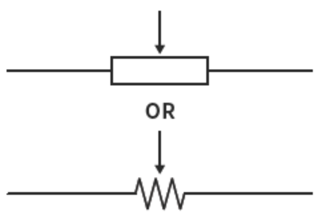


Figure 9 The circuit diagram symbols for a potentiometer

Thermistors

Thermistors are variable resistors whose resistance varies with temperature. While all resistors are affected by temperature, thermistors are much more sensitive, so their resistance varies more significantly.

Thermistors can increase **or** decrease resistance with increasing temperature. The resistance of a thermistor at a specific temperature must be read from its resistance-temperature graph. For example, if we were told that the thermistor represented in Figure 11 was at 25°C, we would use the graph to determine it has a resistance of 10 kΩ.

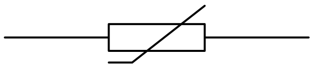


Figure 10 The circuit diagram symbol for a thermistor

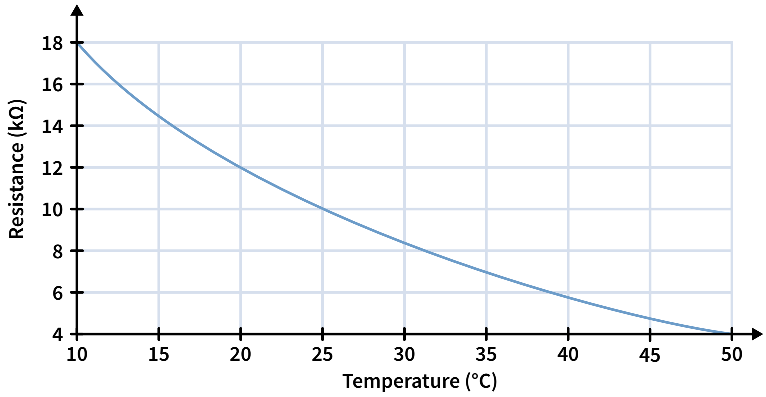


Figure 11 An example of a resistance-temperature graph for a thermistor

Light-dependent resistors

Light-dependent resistors (LDRs), also known as photoresistors, are a type of variable resistor where the resistance decreases as the intensity of light hitting its sensitive surface increases.

Like thermistors, a graph (in this case a resistance-light intensity graph) must be used to determine the resistance of an LDR for a given light intensity.

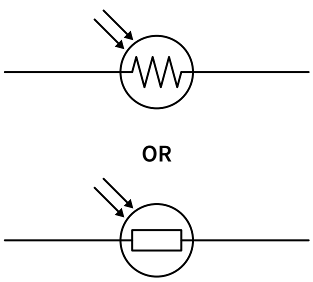


Figure 12 The circuit diagram symbols for a light-dependent resistor

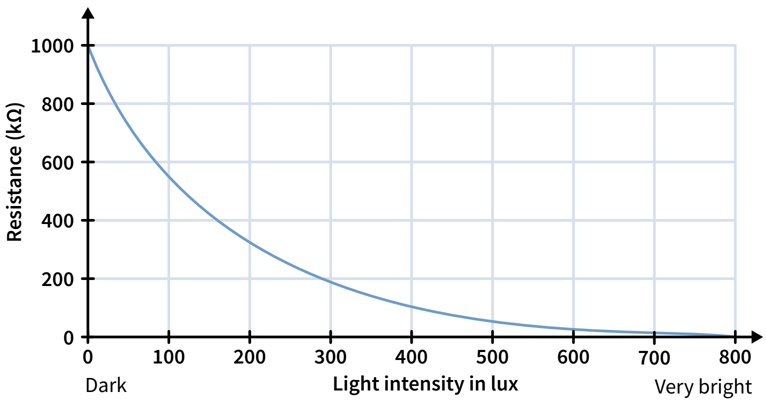


Figure 13 An example of a resistance-light intensity graph for a thermistor

Transducers

A transducer is any device that is designed to convert energy between different forms. An electric component (such as an LED, microphone, or motor) or a circuit itself can be a transducer. Transducers are important parts of electric circuits, often acting as sensors or outputs of a circuit. A common way that transducer circuits are constructed is using a variable resistor in a voltage divider to transform an input energy – such as thermal energy or light – into an electric signal with electrical potential energy.

In such a voltage divider, a variable resistor can be either the output resistor or the other resistor. Figure 14 is an example of using a thermistor as the other resistor.

If we choose a thermistor whose resistance decreases with temperature, the output voltage of the divider will increase with temperature. In this way, we have essentially created a digital thermometer. A switching circuit that turns on at a certain voltage can then be used to operate additional components when a certain temperature (and thus voltage) is reached. A transducer like this could be used as a temperature sensor in the control system of an air conditioner.

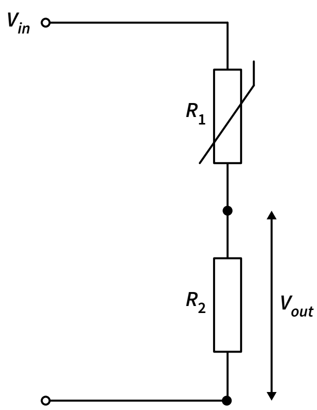
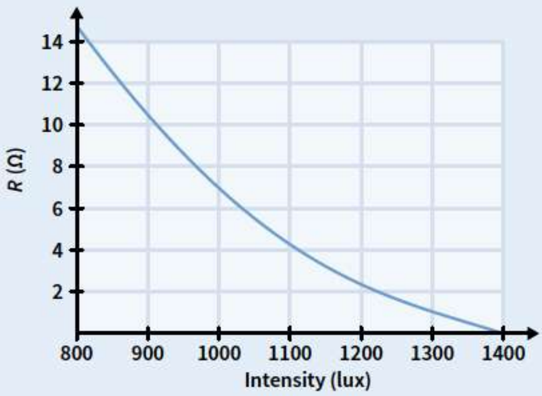


Figure 14 Using a thermistor in a voltage divider circuit to create a digital thermometer

Worked example 3

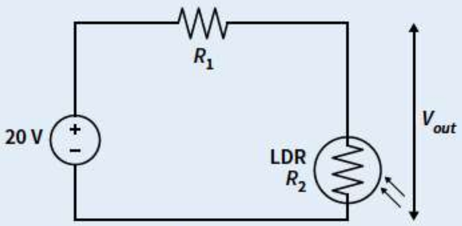
A light intensity sensor is required to operate a street lamp.

- Design a voltage divider circuit consisting of an LDR with the resistance-intensity relationship shown in the graph below, another resistor (of any value), and a 20 V ideal source.
- The circuit should output 10 V when the light intensity is 1000 lux.
- For light intensities above 900 lux, the voltage output should be smaller than 10 V.



Working

Circuit design:



Process of thinking

As the output voltage must decrease for greater light intensity, make the LDR R_2. The decrease in resistance for greater intensity will cause a decrease in voltage dropped across it (as the voltage divider equation tells us $V_{out} \propto \frac{R_2}{R_1 + R_2}$).

At 1000 lux, $R_2 = 7.0\ \Omega$

$$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$$

$$10 = \frac{7.0}{R_1 + 7.0} \times 20$$

$$R_1 = 7.0\ \Omega$$

Determine the LDR resistance at 1000 lux. Use this value of R_2 with the required output voltage (10 V) in the voltage divider equation to find the value of R_1.

Theory summary

- Voltage dividers use the ratio between two resistors to output a voltage that is smaller than the input voltage.
  - $V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$
- Power sources have internal resistance which affects the voltage and current that can be provided to a circuit.
  - Internal resistance is modelled as a resistor R_i in series with the source.
- Light bulbs have a variable resistance that depends on the operating voltage.
- Diodes are semiconductor devices that only allow current to flow one way through them.
  - A small voltage drop occurs across a diode.
- Light-emitting diodes (LEDs) are a type of diode that emits light when a forward voltage is applied.
  - The current through an LED must be limited to avoid its failure.
- Potentiometers are variable resistors whose resistance can be manually controlled by physically moving a contact along a resistive material.
- Thermistors are variable resistors whose resistance varies with temperature.
- Light-dependent resistors (LDRs) are variable resistors whose resistance varies depending on the amount of light hitting their light-sensitive surface.
- To analyse circuits containing diodes and/or variable resistors, interpreting data from graphs displaying their behaviour is often required.

KEEN TO INVESTIGATE?

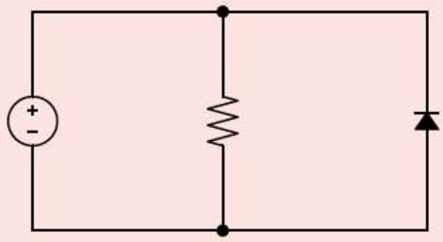
PhET 'Circuit Construction Kit' simulation
phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab

YouTube video: Engineering Mindset – Diodes Explained
youtu.be/Fwj_d3uO5g8

CONCEPT DISCUSSION QUESTION

Discuss the effect on the operation of a simple resistive circuit when a diode is placed in parallel with the circuit, as shown in the figure. Include discussion on the effect of the diode both when the source is connected as shown and in the reverse direction. Assume the diode is ideal.

Answers on page 505



Hints

When no current flows through the diode, does current flow through the resistor?

Is there a limit to the voltage across the diode when no current is flowing through it?

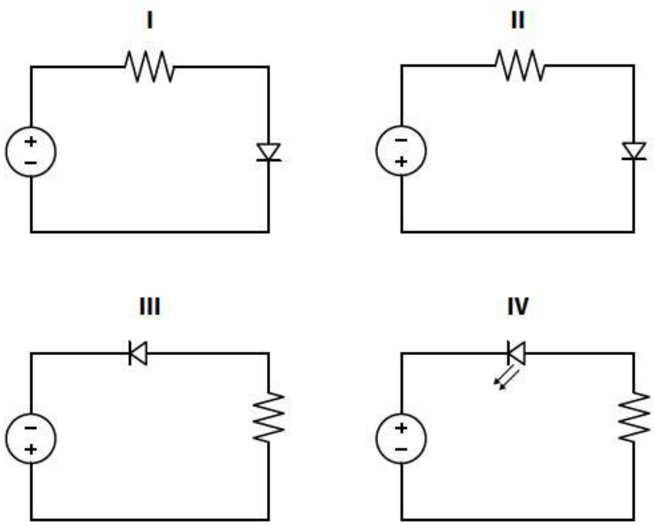
Is there a limit to the voltage across the diode when current is flowing through it?

5A Questions

THEORY REVIEW QUESTIONS

Question 1

In which of these four circuits will a current flow?
(Select all that apply)



Question 2

A diode is placed into a series circuit. Assuming current is flowing, the total current in the circuit will

A decrease due to the voltage drop across the diode.

B increase due to the voltage drop across the diode.

C be unchanged.

Question 3

When designing a voltage divider with a variable resistor, the variable resistor should always be the output resistor, R_2.

A True

B False

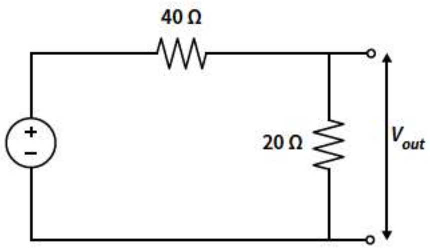
Question 4

Fill in the gaps in the following paragraph about internal resistance.

The internal resistance of a source is an inherent property of __________ (real/ideal) sources. It limits the __________ (maximum/minimum) current that can be provided by the source. When the load resistance is similar in magnitude to the internal resistance, there is a __________ (negligible/significant) effect on the voltage supplied to the load due to the internal resistance.

Question 5

Will the output voltage of this voltage divider be more than or less than half of the input voltage?



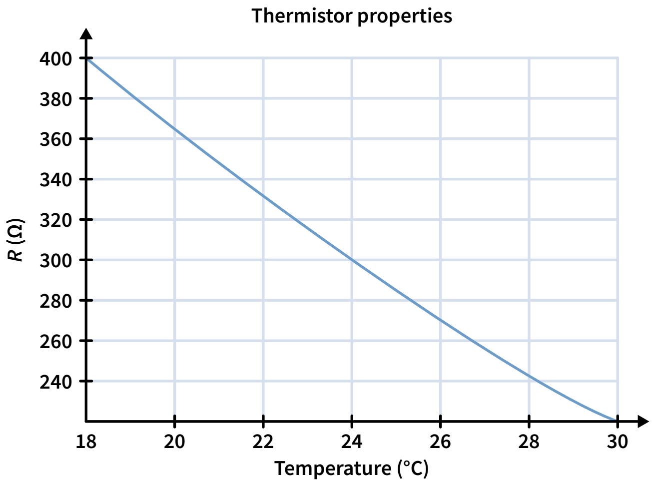
A More than

B Less than

DECONSTRUCTED EXAM-STYLE QUESTION

Question 6 (4 MARKS)

An engineer is designing the circuitry of an air conditioner. She has a 12.0 V source with an internal resistance of 1.00 Ω, a thermistor represented by the graph below, and a potentiometer with a range of 200–1000 Ω.



Prompts

a What is the resistance of the thermistor at 24°C?

A 200 Ω

B 300 Ω

C 350 Ω

D 250 Ω

b If we want to create a voltage divider that increases the output voltage with temperature, should the thermistor be the output resistor R_2?

A Yes

B No

c To output a voltage of 5.00 V, the ratio $\frac{R_2}{R_1 + R_2}$ of a voltage divider with a 12.0 V source needs to be equal to:

A $\frac{1}{2}$

B $\frac{1}{3}$

C $\frac{12}{5}$

D $\frac{5}{12}$

Question

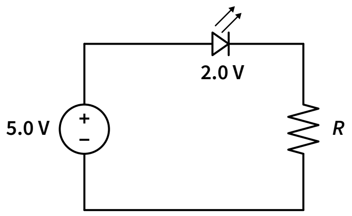
d Design a circuit using the circuit elements the engineer has available that will output a voltage of 5.00 V at 24°C, and above 5.00 V for temperatures above 24°C. (4 MARKS)

EXAM-STYLE QUESTIONS

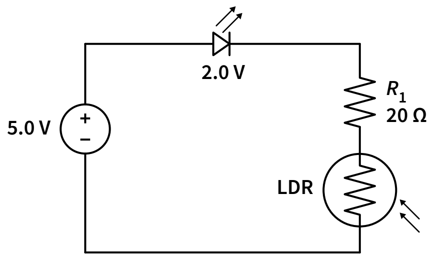
This lesson

Question 7 (2 MARKS)

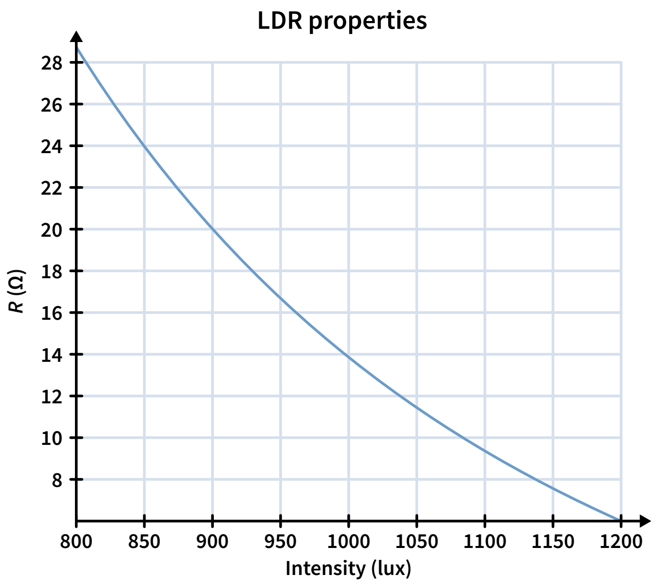
An LED has a threshold voltage of 2.0 V and a maximum current of 20 mA. If it is to be powered with a 5.0 V source, what is the minimum resistance that could be used as a current-limiting resistor in the circuit shown?

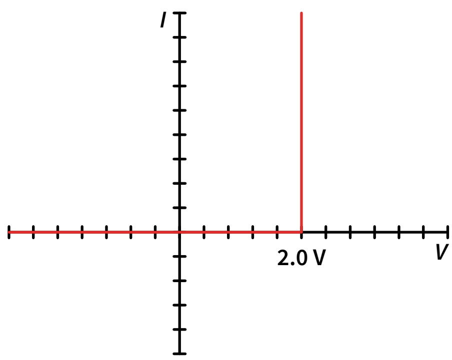


Question 8 (4 MARKS)



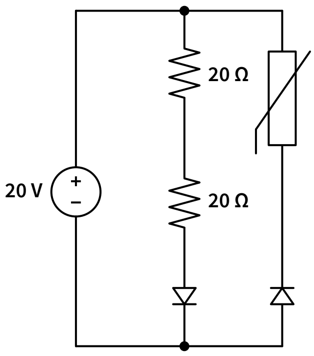
Determine the voltage drop across the LDR in this circuit when the light intensity is 900 lux. The LDR and LED characteristics are represented by the graphs below.





Question 9 (1 MARK)

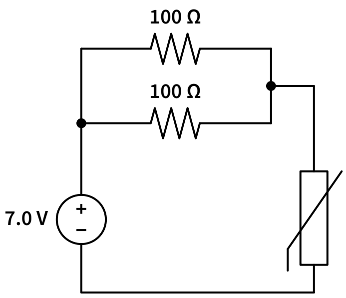
What is the current flowing through the thermistor in this combination circuit?



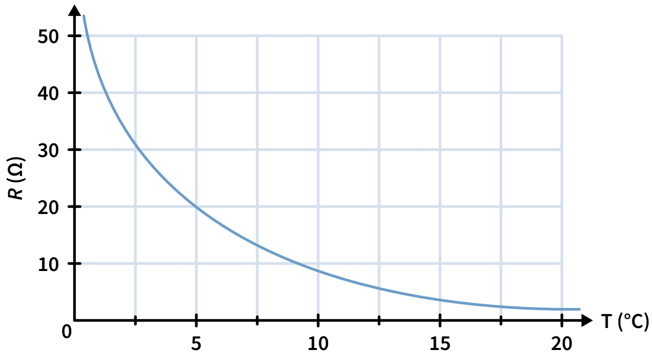
Question 10 (2 MARKS)

Explain the effect of an internal resistance on the voltage and current that can be provided by a voltage source, compared to if the source was ideal.

Question 11 (3 MARKS)

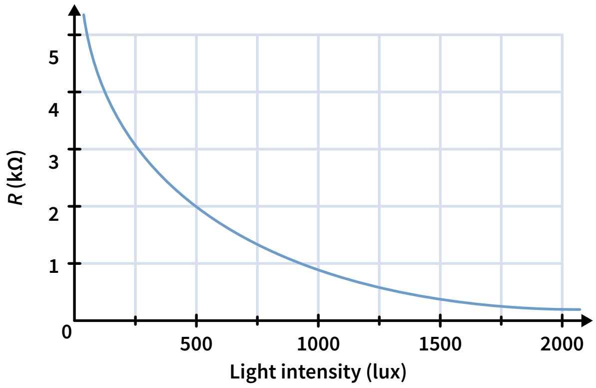


Determine the temperature of the thermistor in this circuit when a current of 100 mA is being provided by the source. The properties of the thermistor are shown in the graph below.



Question 12 (4 MARKS)

Using an LDR with characteristics of the graph below, a potentiometer with a range of 40–4000 Ω, and a 300 V ideal source, design a circuit that will output 100 V when the intensity of light hitting the LDR is 500 lux, and which decreases the output voltage as intensity **decreases**.



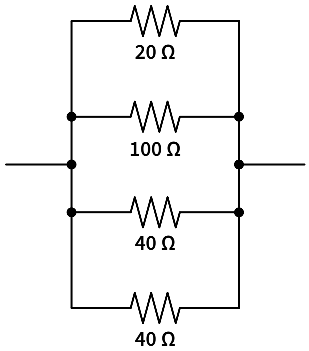
Previous lessons

Question 13 (2 MARKS)

Compare the interactions of solar radiation and Earth's radiation when they encounter greenhouse gases.

Question 14 (2 MARKS)

Calculate the equivalent resistance of the parallel resistors shown in the diagram.



Key science skills

Question 15 (2 MARKS)

Explain what it means for an experiment to be valid, and list the stages of experimentation which affect validity.

5B HOUSEHOLD ELECTRICITY

The electricity delivered to a household is known as alternating current, which is different from the direct current we encountered in Chapter 4. In this lesson, we will learn how alternating current is different and how those differences affect the wiring in household electrical systems. We will also learn a new energy unit that is commonly used when measuring household energy consumption.

5A Applications of electric circuits	5B Household electricity	5C Electrical safety

Study design dot points

- apply the kilowatt-hour (kW h) as a unit of energy.
- model household (AC) electrical systems as simple direct current (DC) circuits
- explain why the circuits in homes are mostly parallel circuits

Key knowledge units

The kilowatt-hour	1.2.5.1
Alternating current	1.2.8.1
Household electrical systems	1.2.8.2 & 1.2.10.1

Formulas for this lesson

Previous lessons		New formulas
4A	$P = \frac{E}{t}$	$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$ RMS voltage
4A	$P = VI$	$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$ RMS current
4B	$V = IR$	

Definitions for this lesson

AC (alternating current) electricity electricity with a periodically alternating direction of current and voltage

active wire the wire at the end of an AC electrical system with a varying potential; this wire connects to the voltage supply

DC (direct current) electricity electricity with a constant direction of current and voltage

live wire see 'active wire'

neutral wire the wire at the end of an AC electrical system that is fixed at zero volts; this wire connects to the ground

RMS (root-mean-square) a measure of a time-varying (such as AC) voltage or current. A constant DC voltage or current with the same value as the RMS would deliver the same average power

The kilowatt-hour 1.2.5.1

OVERVIEW

A kilowatt-hour is a unit of energy. It is commonly used for measuring large quantities of energy such as the amount of electrical energy used by a household over a month.

THEORY DETAILS

In Lesson 4A we learned that power is the rate of change of energy per unit of time: $P = \frac{E}{t}$. Alternatively we could write: $E = P \times t$. We also learned that the SI unit for measuring power is the watt, where one watt is equivalent to one joule per second ($1\ \text{W} = 1\ \text{J s}^{-1}$).

If an appliance operates with a power of one kilowatt (1000 W) for one hour (3600 s), then we could determine that the amount of energy used by the appliance is given by $E = P \times t = 1000 \times 3600 = 3.6 \times 10^6$ J.

This quantity of energy is also called one kilowatt-hour.

$$1\ \text{kW h} = 3.6 \times 10^6\ \text{J}$$

It is important to recognise that the kilowatt-hour is simply another unit for measuring energy. It is most commonly used for measuring large quantities of electrical energy. It is not a measure of power.

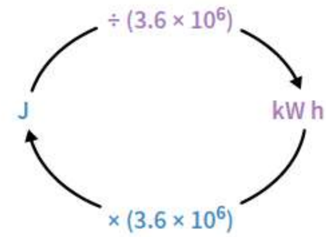


Figure 1 Conversion factor between kilowatt-hours and joules

Worked example 1

An electric oven operates with a power of 0.70 kW for 30 minutes while baking a cake.

a Determine the amount of energy used by the oven in kilowatt-hours.

b Determine the amount of energy used by the oven in joules.

Working	Process of thinking
a $E = P \times t$	Identify the relationship between energy, power, and time.
$E = 0.70 \times 0.50$	The answer is to be provided in kW h so it is simplest to use kilowatts for the power and hours for the time.
$E = 0.35$ kW h	$P = 0.70$ kW, $t = \frac{30\ \text{min}}{60\ \text{min/h}} = 0.50$ h
b $E = 0.35 \times 3.6 \times 10^6$ J	To convert from kilowatt-hours to joules, we multiply by 3.6×10^6.
$E = 1.26 \times 10^6 = 1.3 \times 10^6$ J	We could obtain the same answer by converting power to watts and the time to seconds before applying $E = P \times t$.

Alternating current 1.2.8.1

OVERVIEW

Alternating current (AC) describes electricity where the charges repetitively change direction. This means that the value of the voltage and the current changes from one instant to the next. We commonly use the root-mean-square to describe AC quantities.

THEORY DETAILS

What is alternating current?

The electricity from a battery is called direct current (DC) because the electrons flow in a constant direction. To produce DC electricity, the potential difference between the two terminals of the battery is fixed. For example, for a 12 V battery, the positive terminal is always 12 V higher than the negative terminal so that conventional current always flows from the positive terminal to the negative terminal.

The electricity used in a household is called alternating current (AC) because the electrons change direction, moving back and forth. If DC is like the teeth on a chainsaw, moving in one direction around a loop to cut through wood, then AC is like the teeth on a hand saw moving back and forth. To produce AC electricity, the potential difference between the two ends of the circuit constantly changes.

- The **active wire** (also called the **live wire**) is the end of the circuit that connects to the AC voltage supply. It varies between a positive maximum value and a negative maximum value, which is due to the way the electricity is generated at the power station. For example, in Australian households, the active wire varies between around +340 V and –340 V.
- The **neutral wire** is ultimately connected to the ground (the Earth), which is at 0 V.
- When the active wire is at +340 V, conventional current flows from the active wire through the circuit to the neutral wire. When the active wire is at –340 V, conventional current flows from the neutral wire through the circuit to the active wire. Remember that electrons flow in the opposite direction to conventional current. Compare Figure 2 in this lesson, which represents the changing potential and changing movement of electrons in an AC circuit, with Figure 9 from Lesson 4A.

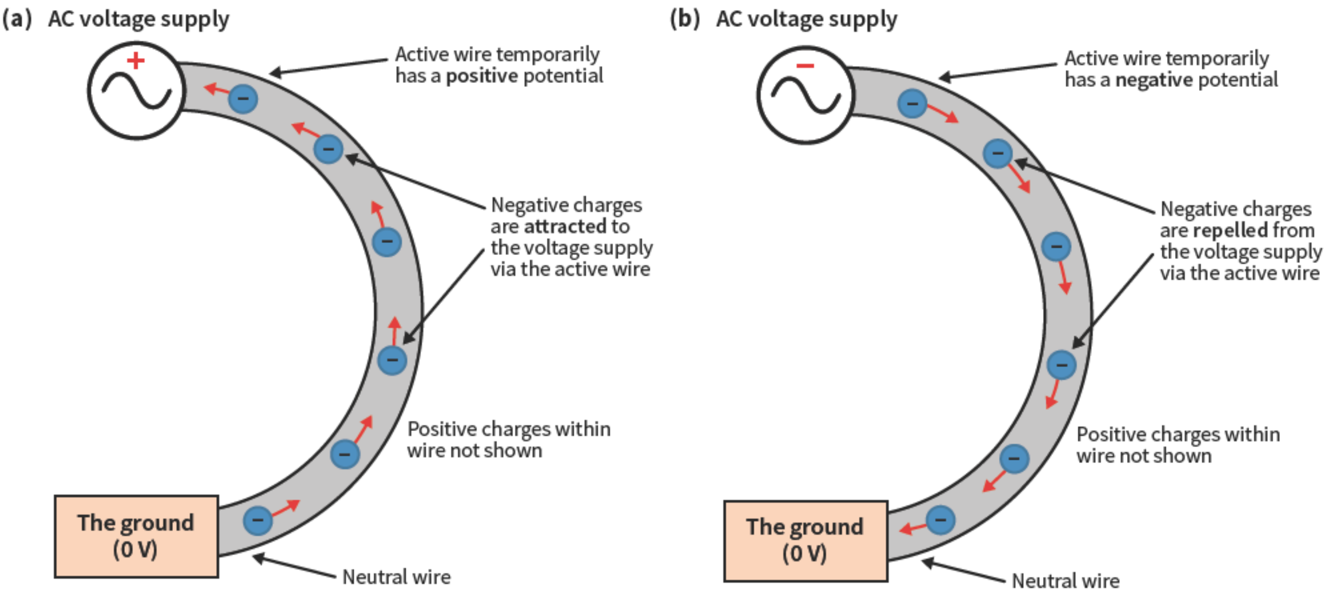


Figure 2 **(a)** When the active wire is at a positive potential, electrons flow towards it (conventional current flows away from it). **(b)** When the active wire is at a negative potential, electrons flow away from it (conventional current flows towards it).

It is worth noting that, unlike a DC circuit, the path along which alternating current flows does not form a complete circuit because the active wire and the neutral wire lead to different places. However it is still common to refer to an AC system as a 'circuit'.

Comparing AC and DC electricity

The voltage, and hence current, supplied to household electrical systems varies sinusoidally, as shown in Figure 3.

We often use the root-mean-squared (RMS) values of voltage and current to describe sinusoidal AC electricity. The RMS value is a fixed proportion of the peak value (as shown in Figure 3) which can be calculated as follows:

$$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$$

V_{RMS} = root-mean-square voltage (V), V_{peak} = peak voltage (V)

$$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$$

I_{RMS} = root-mean-square current (A), I_{peak} = peak current (A)

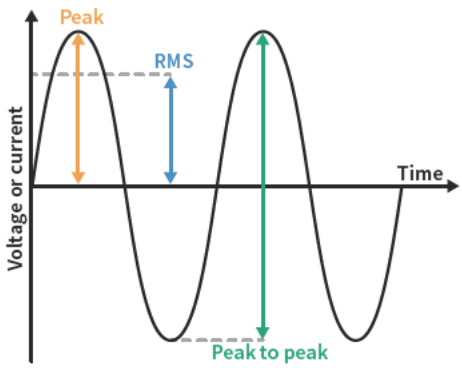


Figure 3 A voltage (or current) versus time graph with indications of peak, peak-to-peak, and RMS values

An RMS value has the same magnitude as the constant DC value that would deliver the same average amount of power. For example, consider a light bulb rated at 12 V. If we use a DC source, such as a battery, to supply power to the light bulb, we would require a constant 12 V source for the light bulb to operate properly. To deliver the same power to the same light bulb with an AC source, we require a 12 V RMS source (which has a peak value of 17 V to two significant figures).

The equations that were introduced throughout Chapter 4 for DC electricity also apply to the RMS values of AC electricity.

Worked example 2

The peak AC voltage delivered to a toaster is 340 V. The resistance of the toaster is 40 Ω.

a Determine the RMS voltage supplied to the toaster.

b Determine the RMS current supplied to the toaster.

c Determine the constant DC voltage that would deliver the same average power.

d Calculate the average power delivered to the toaster.

Working	**Process of thinking**
a $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$ $V_{RMS} = \frac{1}{\sqrt{2}} \times 340 = 240\text{ V}$	Identify the relationship between peak AC voltage and the RMS voltage.
b $I_{RMS} = \frac{V_{RMS}}{R}$ $I_{RMS} = \frac{240}{40} = 6.0\text{ A}$	Identify the relationship between current and voltage using Ohm's law. Both current and voltage must use RMS values.
c 240 V DC	By definition, the RMS value is the same as the constant DC value that would deliver the same average power.
d $P = V_{RMS} I_{RMS}$ $P = 240 \times 6.0$ $P = 1.4 \times 10^3\text{ W}$	Identify the relationship between power, current, and voltage. Both current and voltage must use RMS values.

Household electrical systems 1.2.8.2 & 1.2.10.1

OVERVIEW

Household electrical systems use alternating current. Most appliances and power points in households are wired in parallel. We can model these parallel circuits like simple DC circuits.

THEORY DETAILS

The wiring for a typical household consists of a distribution board (also called a switch box, fuse box, or panel board), to which the active and neutral supply wires are connected from the street, and multiple parallel circuits called 'circuit rings'. The distribution board has a main switch (which can disconnect the entire household electrical system), fuses or circuit breakers, residual current devices, a meter, and some other instruments. Each circuit ring is distributed from the distribution board via a fuse or a circuit breaker.

A circuit ring services a section of the house such as the lights in a given area or the power outlets. Within a circuit ring, individual appliances or power outlets are also connected in parallel. An earth wire connects one of the pins in each power outlet to a metallic stake in the ground.

The three types of wires in a household circuit are colour coded: the active wire is brown, the neutral wire is blue, and the earth wire is green or green and yellow. The role of fuses, circuit breakers, and residual current devices (which are all located at the distribution board), as well as the earth wire, will be covered in Lesson 5C.

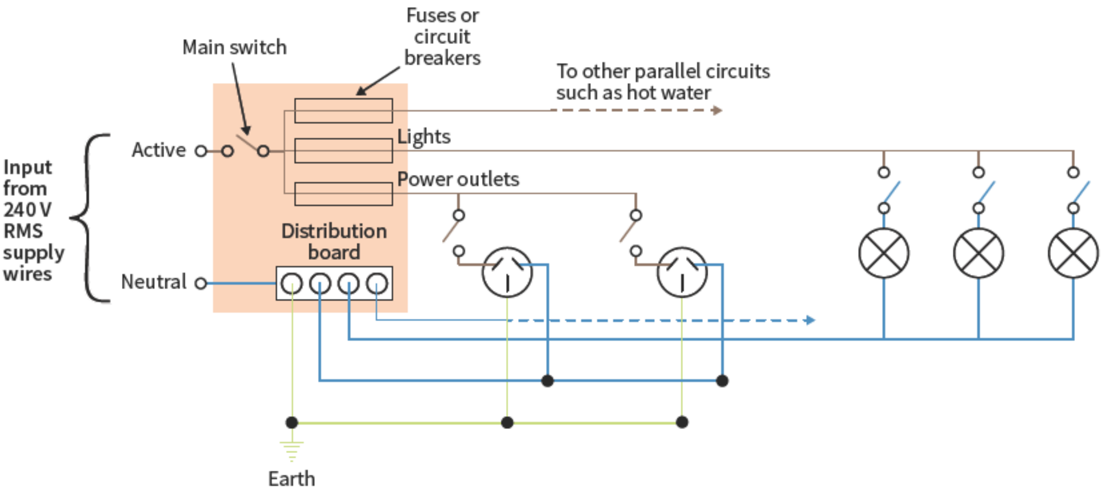


Figure 4 A household wiring diagram showing circuit rings for lights and power outlets. Within each circuit ring, individual appliances or power outlets are connected in parallel.

The circuits in a household system are mostly connected in parallel to allow individual appliances to be switched on or off without affecting the operation of other appliances. If there is a fault in one of the circuit rings (such as an open circuit breaker, which will be covered in Lesson 5C), then only appliances on that circuit ring will be affected but other circuit rings will not be affected.

While the nature of alternating current has some important differences to simple DC circuits, it is common to model AC household electrical systems as simple parallel DC circuits. Figure 5 shows a DC circuit model of the household wiring diagram in Figure 4.

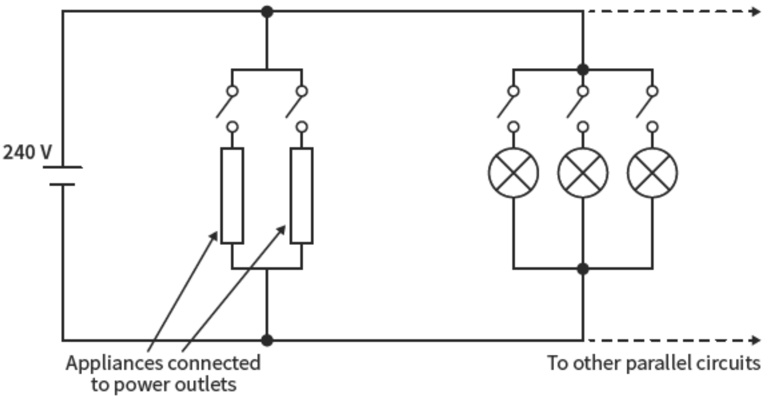


Figure 5 A simple DC circuit model of the household wiring shown in Figure 4

Theory summary

- One kilowatt-hour is the amount of energy used by an appliance that has a power of one kilowatt when it is used for one hour.
  - $1 \text{ kW h} = 3.6 \times 10^6 \text{ J}$
- For AC electricity:
  - The charges (electrons) constantly change direction.
  - An active wire varies between a positive potential and a negative potential while a neutral wire maintains a fixed potential of 0 V by connecting to the ground.
  - RMS values of AC voltage and current indicate the DC voltage or current that would deliver the same amount of power.
  - $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$ and $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$
- Household electrical systems use alternating current with most appliances connected to parallel circuits to allow their individual operation.
- The principles for analysing circuits that we learned in Chapter 4 apply to household (AC) electrical systems so it is common to model them as simple DC circuits.

KEEN TO INVESTIGATE?

PhET 'AC circuit construction' simulation
phet.colorado.edu/sims/html/circuit-construction-kit-ac/latest/circuit-construction-kit-ac_en.html

PhET 'Generator' simulation
phet.colorado.edu/en/simulation/generator

YouTube video: AddOhms – Difference between AC and DC
youtu.be/vN9aR2wKv0U

YouTube video: Chris Mahl – AC vs DC
youtu.be/BcIDRet787k

YouTube video: Educational Video Library – What is Alternating Current?
youtu.be/q-DKc4KHPqU

YouTube video: The Life Guide – Nikola Tesla Explained in 16 Minutes
youtu.be/Ok8JDXSYw1U

CONCEPT DISCUSSION QUESTION

While a household electrical system uses alternating current, some electronic appliances – especially those that store and process information such as mobile phones and computers – convert AC to DC. But appliances that simply convert electrical energy into another form of energy generally can run on AC.

Discuss how AC can transfer electrical energy from the source to the appliance even though the individual charges (electrons) only move back and forth by very small distances. Use a hand saw as an analogy in your discussion.

Answers on page 505

Hints

How does a hand saw cut through wood?

What provides energy most immediately to the hand saw for it to cut through wood?

Do the hand saw's teeth need to move from this place to the wood, for this process to occur?

How is electrical energy transformed into other types of energy, such as thermal energy in a toaster?

Do charges need to move from the source to the appliance for this process to occur?

5B Questions

THEORY REVIEW QUESTIONS

Question 1

What does a kilowatt-hour measure?

A Energy

B Power

C Power per unit of time

Question 2

How much energy is used by an electric oven that operates at 3.0 kW for 2.0 hours?

A 1.5 kW h

B 6.0 kW h

Question 3

2.0 kW h is equivalent to

A 5.6×10^{-7} J.

B 1.8×10^{6} J.

C 7.2×10^{6} J.

Question 4

Which of the following statements is true?

A The 'active wire' is the name given to the positive terminal in an AC circuit and the 'neutral wire' is the name given to the negative terminal.

B The 'active wire' is the name given to the negative terminal in an AC circuit and the 'neutral wire' is the name given to the positive terminal.

C The active wire varies between having a positive potential and a negative potential. The neutral wire is fixed at 0 V.

Question 5

Which of the following statements is true?

A The direction of current changes in an AC circuit.

B In an AC circuit, conventional current always flows from the active terminal to the negative terminal.

C In an AC circuit, conventional current always flows from the negative terminal to the positive terminal.

Question 6

The potential in the active wire of an AC electrical system varies between +200 V and –200 V. Which of the following is closest to the DC voltage that would deliver the same average power?

A $\frac{1}{\sqrt{2}} \times 200 = 141$ V

B 200 V

C $200 \times \sqrt{2} = 283$ V

D 400 V

Question 7

Which of the following is the best reason for why circuits in homes are mostly parallel circuits?

A Parallel connections use less energy so they are cheaper and better for the environment.

B Parallel circuits allow individual appliances to be switched on or off without affecting other appliances.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (3 MARKS)

An electric heater has a resistance of 80 Ω. It is connected to an AC electrical system so that the peak voltage across it is 300 V. It operates for 4.0 hours.

Prompts

a Which of the following is closest to the RMS voltage across the heater?

A 212 V

B 300 V

C 424 V

D 600 V

b How is the RMS voltage related to the power consumption of the heater?

A $P = V_{RMS} R$

B $P = V_{RMS} \times t$

C $P = \frac{V_{RMS}^2}{R}$

D $P = \frac{V_{RMS}}{I}$

c How is the energy use related to the power consumption and the time of operation?

A $E = \frac{P}{t}$

B $E = P \times t$

C $E = P^2 \times t$

D $E = \frac{t}{P}$

Question

d Calculate the energy used by the electric heater over this time. Provide your answer in kilowatt-hours. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (3 MARKS)

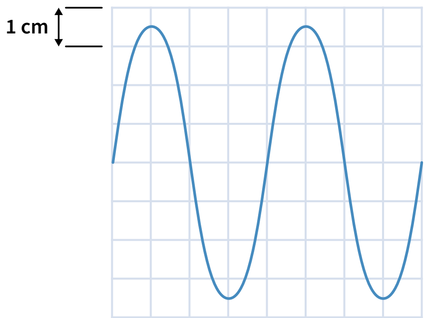
A microwave oven heats a meal in 6.0 minutes and uses 0.16 kW h in that time.

a Determine the power of the microwave oven in kilowatts. (2 MARKS)

b How much energy is used by the microwave oven over the 6.0 minute-period in joules? (1 MARK)

Question 10 (2 MARKS)

Rex is measuring the voltage from an AC signal generator using an oscilloscope, which produces the following output. The vertical scale is set to 0.4 V cm^{-1}.



Calculate the value of the constant DC voltage that would deliver the same power as this signal generator.

Adapted from 2010 VCAA Exam 1 Section B Detailed study 3 Q4

Question 11 (2 MARKS)

The power outlets and fixed appliances in a household are usually connected in parallel. Explain how the operation of the lights in a household would be different if they were all connected in series.

Question 12 (5 MARKS)

An electric appliance with a resistance of 50 Ω uses an average of 242 W while operating on a household electrical system.

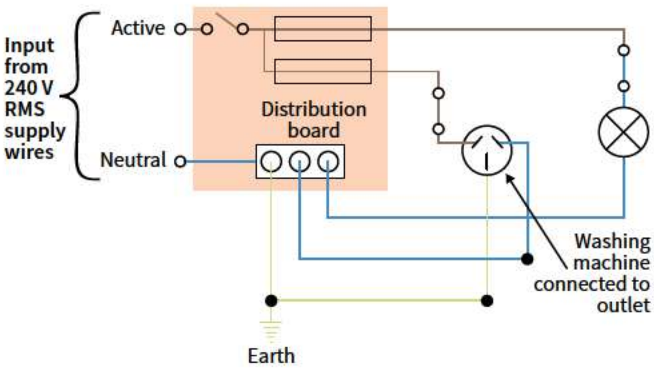
a Show that the RMS current flowing through the appliance is 2.2 A. (2 MARKS)

b Calculate the peak current flowing through the appliance. (1 MARK)

c How much energy is used by the appliance if it is operating for 2.5 hours? Provide your answer in kilowatt-hours. (2 MARKS)

Question 13 (5 MARKS)

A household electrical system is supplied by 240 V_{RMS}. Within the system there is a 60 W lamp operating correctly and a washing machine that is connected to one of the power outlets as shown. For its current operation, the washing machine can be considered to have a resistance of 120 Ω. There are no other electrical devices operating and you can ignore the resistance of the wires.



a Draw a circuit diagram to model the household electrical system as a simple DC circuit. The washing machine should be represented with a resistor symbol. Include the relevant values provided. (2 MARKS)

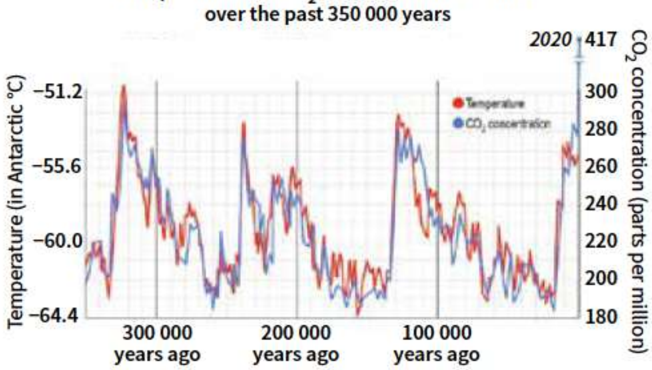
b Calculate the RMS value of the current flowing through the supply wires in this situation (3 MARKS).

Previous lessons

Question 14 (7 MARKS)

Data from the last 300 thousand years indicates a correlation between the Earth's atmospheric carbon dioxide levels and the global average temperature. An example of such data is shown by the included graph.

Temperature and CO_2 from Antarctic ice cores over the past 350 000 years



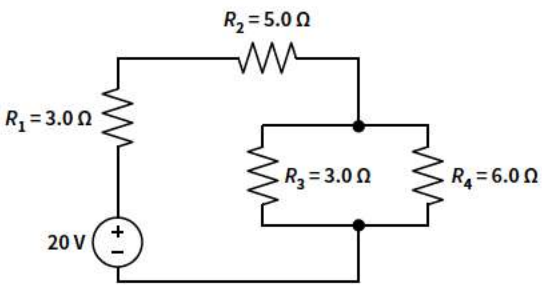
a Explain why this correlation, by itself, does not indicate that changes in carbon dioxide levels cause changes in global temperatures. Include an explanation of what is meant by 'correlation' in your response. (2 MARKS)

b The relationship between carbon dioxide levels and global temperatures is well understood due to data that has been collected from other scientific experiments and scientific theory. Explain this relationship in terms of feedback. (2 MARKS)

c How does more recent data provide evidence that human activity is causing the enhanced greenhouse effect? (3 MARKS)

Question 15 (5 MARKS)

The diagram shows a circuit consisting of four resistors and a 20 V power supply.



a Show that the total effective resistance of the circuit is 10.0 Ω. (2 MARKS)

b Calculate the current flowing through resistor R_4. (3 MARKS)

Key science skills

Question 16 (4 MARKS)

Arden and Jacinta take measurements of the energy used by a kettle to boil 2.0 litres of water.

	Jacinta's measurements (kW h)	Arden's measurements (kW h)
Meas. 1	0.15	0.18
Meas. 2	0.23	0.18
Meas. 3	0.25	0.20
Meas. 4	0.19	0.20
Meas. 5	0.19	0.18

The true value for each measurement is 0.19 kW h.

a Which set of data (Jacinta's or Arden's) is more accurate? Justify your answer. (2 MARKS)

b Which set of data (Jacinta's or Arden's) is more precise? Justify your answer. (2 MARKS)

5C ELECTRICAL SAFETY

Electrical faults are one of the most common causes of house fires. While electricity is an incredibly important feature of our modern lives, it also has the potential to cause great harm. This lesson will explore some of the common designs used in household circuits to protect people from the risks associated with using electricity as well as describing the causes and effects of those risks.

5A Applications of electric circuits	5B Household electricity	5C Electrical safety

Study design dot points

- model household electricity connections as a simple circuit comprising fuses, switches, circuit breakers, loads and earth
- compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs)
- describe the causes, effects and treatment of electric shock in homes and identify the approximate danger thresholds for current and duration

Key knowledge units

Safety features in household circuits	1.2.14.1 & 1.2.15.1
Electric shock	1.2.16.1

No previous or new formulas for this lesson

Definitions for this lesson

circuit breaker a safety device that opens a resettable switch, causing a break in an electric circuit, when too much current flows through it

earth wire the third wire that connects to household appliances, which provides a low-resistance path for current to flow from the outside of the appliance to the ground in order to avoid an electric shock

electric shock the sensation and damage done when electric current flows through a person or other living thing

fuse a safety device that melts, causing a break in an electric circuit, when too much current flows through it

residual current device (RCD) a safety device that switches off a household electric circuit when it detects a difference between the current flowing in the active and neutral wires

short circuit a situation in which current skips part of a circuit by following an unintended path with very low resistance, causing a larger current to flow

Safety features in household circuits 1.2.14.1 & 1.2.15.1

OVERVIEW

Fuses are designed to permanently break a circuit when the current exceeds a certain value. Circuit breakers perform a similar function but they can be reset. Residual current devices switch off circuits if they detect leaking current. The earth wire directs current that incorrectly flows through the exterior of an appliance towards the ground to avoid it flowing through people.

THEORY DETAILS

The electric circuits in a household must be able to deliver a lot of electrical energy in order to provide heating and cooling, lighting, and running other appliances. Energy can be understood as the ability to do things, which means this tremendous amount of electrical energy also has the capacity to do tremendous harm if it is not properly managed.

In particular, this energy is dangerous for two reasons:

- When too much current flows through a circuit it can damage the appliances in the circuit and overheat the wires, which can start a fire.
- When electricity flows through a person, it can (potentially fatally) damage the tissue and organs that it flows through, which is known as **electric shock**.

This section will explore the function of four common safety features in Australian household electrical circuits.

Fuses

The purpose of a fuse is to prevent overheating and damage to appliances due to the current in a circuit exceeding a certain value. A surge in current within a circuit is most likely caused by a short circuit (such as exposed active and neutral wires coming into contact), which greatly reduces the overall resistance of the circuit. A fuse does **not** protect people from electric shock because the current required by most appliances is greater than the amount that would shock (and even kill) people.

A fuse is a built-in 'weak point' that forms part of the relevant circuit. It consists of a thin piece of wire with a higher resistance than the normal wiring in the circuit (but its resistance is still small compared to the total resistance of the circuit). This means it gets hotter than the rest of the circuit wiring. When too much current flows through the circuit, the fuse is designed to melt and break the circuit. Figure 1 shows a new fuse and a melted fuse.

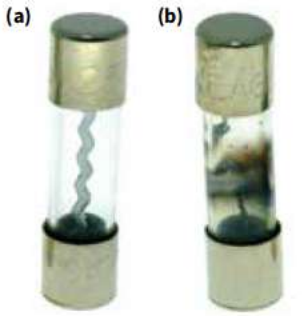


Image: NOPPHARAT6395/Shutterstock.com

Figure 1 **(a)** A new fuse and **(b)** an old fuse that has burnt out due to an overload of current

Fuses are not very common in houses anymore because they need to be replaced when they melt, however they are still common within some appliances and automotive circuits. Circuit breakers are used as an alternative since they can be easily reset.

Circuit breakers

Circuit breakers serve the same purpose as fuses: to prevent fires and damage to appliances. They have largely replaced fuses in household circuits because they do not destroy themselves like a fuse. Instead, they cause a break in the circuit by automatically opening a switch when the current flowing through the circuit exceeds the designed value. When this happens, the circuit breaker switch can be easily reset as shown in Figure 2. Circuit breakers for a given building are usually located all in one place known as a distribution board, breaker panel, or electric panel.

Image: Sutiwat Jutiamornloes/Shutterstock.com

Figure 2 Resetting a circuit breaker switch in the distribution board. The switch in the up position means it is closed, so the circuit can operate.

Residual current devices

A residual current device (RCD) serves a different purpose to fuses and circuit breakers. RCDs are designed to break the circuit when the current is flowing to the wrong place (rather than when too much current is flowing) in order to avoid electric shock. If current flows through a person, then the person provides an alternative pathway for current to flow instead of flowing in the neutral wire. This means there will be less current in the neutral wire than the active wire. An RCD compares the currents in the active wire and the neutral wire (using the magnetic fields created by the current in each wire) for a given circuit in the distribution board. If there is a difference between these two currents, then it will open a switch in less than 0.05 seconds to stop current flowing and prevent harm to the person.

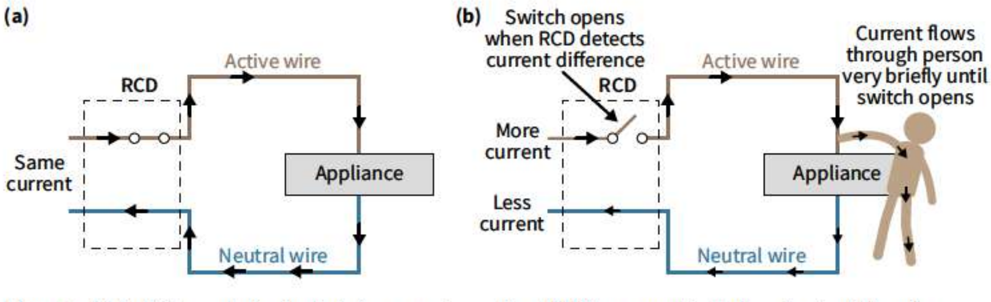


Figure 3 **(a)** An RCD as part of a circuit during normal operation. **(b)** When current leaks from the circuit there is a difference between the currents in the active and neutral wires which causes the RCD switch to open.

Earth wire

An earth wire serves the same purpose as an RCD: to prevent current flowing to the wrong place and causing electric shock. However, an earth wire only protects against the specific risk posed by an active wire coming into contact with the metal exterior of an appliance, which would be caused by a fault such as a cut or frayed wire.

The earth wire provides a direct connection from the metal exterior to the ground (which is why it is called 'earth'). If an active wire touches the exterior of the appliance so that the exterior is 'live', the current will follow a path of least resistance via the earth wire to the ground rather than flowing through a person (who has greater resistance than the earth wire). This is shown in Figure 4. By providing a low resistance path to the ground, the earth wire creates a short circuit when the exterior of an appliance becomes live, which means the circuit breaker (or fuse) will usually be tripped too.

An earth wire does not form part of the circuit (like a fuse) when the circuit is operating normally, and it does not open the circuit or stop current flowing (like an RCD) when there is a problem. It only redirects the current if current happens to flow through the exterior of an appliance.

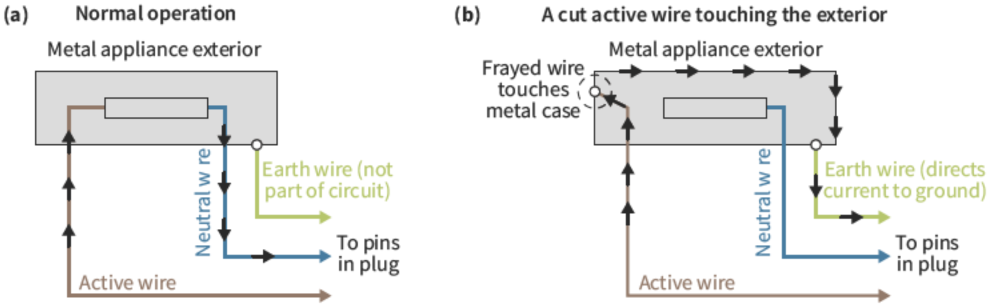


Figure 4 **(a)** The earth wire connects the metal exterior of appliances to the ground but does not do anything when the circuit is operating correctly. **(b)** The earth wire provides a path for current to safely flow from the metal exterior to the ground if the exterior becomes 'live'.

Many modern appliances use double insulation as an alternative to an earth connection (so they do not have the third earth pin on their electrical plugs), which means they have two layers of insulating material between the live wires and the exterior or the exterior itself is made of an insulating material.

Electric shock 1.2.16.1

OVERVIEW

The severity of an electric shock is determined by the amount of current flowing through the person, the duration of the shock, and the path the current takes through the person.

THEORY DETAILS

Despite the safety precautions discussed in the previous section, electrical accidents still occur and pose a dangerous risk. An electric shock occurs when electric current flows through a person. The severity of an electric shock is largely determined by three variables:

- The **amount of current** that flows through the body. A greater current does more damage. The amount of current depends on the voltage of the device and the resistance of the body. For example, the resistance of dry skin is between 10^5 Ω and 10^6 Ω, but it is reduced to around 10^3 Ω when it is wet. This increases the current by a factor of around 100–1000. Wearing rubber gloves and boots with thick soles provides electrical insulation due their very high resistances.
- The **amount of time** that the current flows through the body. A longer time does more damage.
- The **path through the body** taken by the current. Only the parts of the body that form the path can be directly damaged. Greater harm is done when the current passes through vital organs such as the heart.

The frequency of the current also affects the severity of an electric shock. The human body is more sensitive to higher frequencies (up to about 500 Hz) which means that household alternating current that has a frequency of 50 Hz is more dangerous than direct current. Our discussion focuses on electric shocks in homes caused by alternating current.

Effects of electric shock

A very small electric current can pass through the body harmlessly without being felt. Similarly, if current flows for less than about 0.1 seconds (such as the 'zap' due to a discharge of static electricity), it typically will not do harm even if the current is large. By contrast, a shock that lasts for about one second or more can cause severe harm.

A large current can cause muscles to involuntarily and suddenly contract. These contractions can cause a person to appear to be thrown or pushed away from the source, when in fact it is the person's own muscles that cause the movement. If a person suffers an electric shock by gripping a live wire, the electric shock can cause the hand to contract more tightly – since the muscles we use to close our hands are stronger than those used to open them – which prolongs the shock.

If a large current (~100–500 mA) passes through the heart, it can cause the heart to beat irregularly for a prolonged time (persisting longer than the shock itself), known as 'ventricular fibrillation', which is potentially fatal. Even greater currents (~5000 mA or 5 A) cause the heart and diaphragm to contract and remain contracted for the duration of the shock so that blood will not circulate around the body and the person will not breathe in this time. Interestingly, although this is dangerous for any significant duration, a very short pulse of such a large current can be used to defibrillate the heart (return it to a regular beating rhythm).

Whenever electric current passes through an object, some of the energy transforms to thermal energy. For this reason, severe electric shocks are usually accompanied by severe burns.

Table 1 The effects of different amounts of current for a duration greater than ~0.1 seconds

Current (mA)	Effect on body
1	Can just be felt
5	Easily felt, the maximum current that does not do harm
10–50	Muscular contraction, cannot let go during shock, pain
100–200	Ventricular fibrillation possible, breathing upset or difficult, possibly fatal
500	Severe burns, ventricular fibrillation, unable to breathe, likely to be fatal

Treatment for electric shock

Since the duration of an electric shock is an important factor in determining the severity, it is important to ensure that the person who has suffered the shock is no longer connected to the source. If the person is still connected then it is dangerous to touch them so the electric circuit should be switched off and the person should be knocked clear of the source using an object made of insulating material (such as rubber, plastic, or wood).

An ambulance should be called straight away by dialling 000. A defibrillator may need to be used to get the person's heart beating normally again and an artificial respirator may be used if they have stopped breathing. Normal first aid procedures should be followed while waiting for the ambulance to arrive.

Theory summary

Safety device	Main purpose	How it works
Fuse	Prevent fires/damage to circuits	It melts, which breaks the circuit, when current is too high.
Circuit breaker	Prevent fires/damage to circuits	It opens a switch when current is too high.
Residual current device (RCD)	Prevent electric shock	It opens a switch when there is a difference between the current in the active and neutral wires.
Earth wire	Prevent electric shock	It directs current from the outside of an appliance to the ground.

- The severity of an electric shock depends on the amount of current that flows through the person, the amount of time that it lasts, and the path that the current takes through the person.

KEEN TO INVESTIGATE?

Country Fire Authority (2018), Victorian preventable house fire statistics
news.cfa.vic.gov.au/-/victorian-preventable-house-fire-statistics

YouTube video: Warped Perception – How a Circuit Breaker Works in Slow Motion
youtu.be/wGFnooeA6Iw

CONCEPT DISCUSSION QUESTION

Consider what would happen if the earth pin and the neutral pin were swapped in a power outlet so that the appliance was wired between the active wire and the connection to the earth. Discuss whether the appliance will operate as normal and if there are any safety risks in this configuration.

Answers on page 506

Hints

Does this configuration allow current to flow through the appliance?

Will the currents in the active and neutral wires be the same?

Are there any risks associated with the earth forming the endpoint of the circuit?

5C Questions

THEORY REVIEW QUESTIONS

Question 1

When a circuit containing a fuse is operating correctly

A current does not flow through the fuse.

B the fuse forms part of the circuit.

Question 2

A fuse is designed to prevent

A electric shock.

B fires and damage to appliances.

Question 3

A fuse is not an effective protection against electric shock because

A the current required by most appliances, which must also flow through the fuse, is greater than the amount required to cause electric shock.

B there is usually some current left in a circuit, even when the circuit has opened, which can still cause electric shock.

Question 4

When a fuse has opened a circuit due to too much current

A it can be reset.

B it must be replaced.

Question 5

The main **difference** between a circuit breaker and a fuse is that

A circuit breakers can be reset once they have been tripped.

B circuit breakers open a circuit when too much current flows through the circuit.

Question 6

If the current flowing through the active wire is greater than the current flowing through the neutral wire, it indicates that

A current is flowing somewhere that it is not supposed to.

B current is being used up by the appliance.

Question 7

A residual current device opens a circuit when

A there is too much current flowing through the active and neutral wires.

B the device detects different amounts of current in the active and neutral wires.

Question 8

The main purpose of an RCD and the earth wire is to prevent

A electric shock

B fires and damage to appliances.

Question 9

When a circuit is operating correctly

A current does not flow through the earth wire.

B the earth wire forms part of the circuit.

Question 10

Which of the following measurements, by itself, would give the best indication of the severity of an electric shock?

A The voltage applied to the person

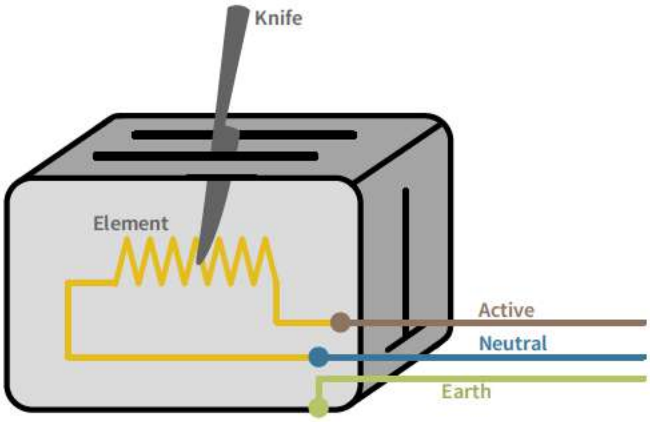
B The amount of current flowing through the person

C The resistance of the person

DECONSTRUCTED EXAM-STYLE QUESTION

Question 11 (3 MARKS)

Regina tries to remove toast that is stuck in the toaster using a metal knife while the toaster is connected and switched on, which is a very dangerous thing to do. Her knife makes contact with one of the elements (a live wire) in the toaster so that current flows through her body to the ground. The amount of current flowing through her body is no greater than the current flowing through the toaster when it is operating normally.



Prompts

a Which of the following statements is true?

- **A** The exterior casing of the toaster is live.
- **B** The current is greater than the amount that the circuit is designed to carry.
- **C** Some or all of the current flowing along the active wire does not flow through the neutral wire.

b What causes a fuse or a circuit breaker to open a circuit?

- **A** Too much current within the intended circuit
- **B** Current leaving the intended circuit
- **C** A live exterior part of an appliance

c What causes current to flow along the earth wire?

- **A** Too much current within intended the circuit
- **B** Current leaving the intended circuit
- **C** A live exterior part of an appliance

d What triggers an RCD to open a circuit?

- **A** Too much current within the intended circuit
- **B** Current leaving the intended circuit
- **C** A live exterior part of an appliance

Question

e Identify which safety design is most likely to protect Regina and explain how it would do this. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 12 (2 MARKS)

The active wire in an appliance that has a metal exterior case is damaged and is making contact with the case. Identify which electrical safety feature is designed to protect against the hazard caused by this particular situation and identify what the hazard is.

Question 13 (5 MARKS)

Polly understands that electric shocks are more severe when the current flowing through the person is greater. She also understands that a short circuit leads to a greater current flowing in the circuit. She concludes that short circuits must be a shock hazard.

a Evaluate Polly's conclusion that a short circuit is a shock hazard. (3 MARKS)

b Why is an RCD an ineffective safety feature for the risk posed by short circuits? (2 MARKS)

Question 14 (4 MARKS)

Current is flowing through the earth connection of a particular appliance. Explain whether (or under what conditions) each of the following safety features would cause a break in the circuit and what hazard the safety feature is designed to protect against.

a A fuse/circuit breaker (2 MARKS)

b An RCD (2 MARKS)

Question 15 (2 MARKS)

Ruth connects a 9 V battery cell to a single light globe. The globe shines brightly and she measures a current greater than 1 A in the circuit. She understands that if 1 A flows through a human it can be deadly. However, she has also been told that touching the terminals of a 9 V battery cell will not cause a severe shock. Explain why touching a 9 V battery cell would not cause a severe shock even though the amount of current it provides to a light bulb could kill a human.

Previous lessons

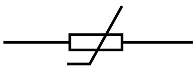
Question 16 (2 MARKS)

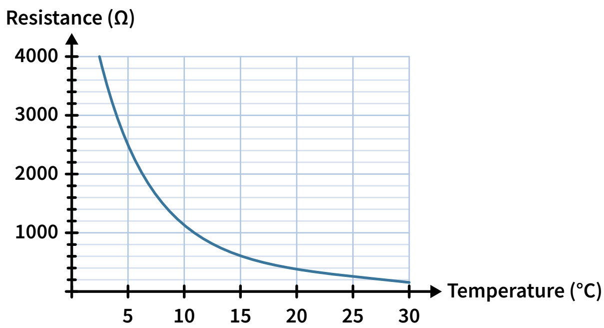
In order to find the change in carbon dioxide concentration in the atmosphere over 10 years, the concentration was measured at the same laboratory in June of each year between 2011 and 2020. Explain why it is important to take the measurements at the same time of year and from the same laboratory.

Question 17 (4 MARKS)

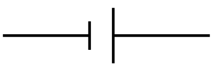
Tyson is installing a small refrigeration system into an esky so that the refrigerator motor turns on when the temperature is **greater** than 5°C. He builds the electric circuit from the following devices.

- A thermistor with the characteristics shown in the graph.

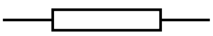




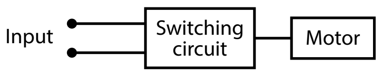
- A 12 V battery



- **One** of the following resistors: 2500 Ω, 5000 Ω, 7500 Ω



- A switching circuit that turns on the refrigerator motor when the voltage across the input is **greater** than 8 V



a What is the resistance of the thermistor when the temperature is 5°C? (1 MARK)

b Using the thermistor, the 12 V battery, and one resistor from the listed resistors, draw a circuit to produce a voltage greater than 8 V at the input of the switching circuit when the temperature is **greater** than 5°C, thus turning the refrigerator motor on. You **must** include the value of the resistor you have used in your diagram. (3 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 2 Q5–6

Key science skills

Question 18 (2 MARKS)

Some students are measuring the current rating of an electrical fuse that is well established to have a rating of 5.0 ± 0.2 A. They take five measurements, as follows: 5.4 A, 5.1 A, 5.5 A, 5.6 A, 5.9 A.

a The students could reasonably describe the measurement uncertainty of their results as about

A 0.2 A

B 0.3 A

C 0.4 A

D 0.8 A

(1 MARK)

b If the manufacturer's rating is taken to be correct, what is the minimum error in the student's average measurement?

A 0 A

B 0.2 A

C 0.3 A

D 0.5 A

(1 MARK)

Adapted from 2017 VCAA Sample Exam Section A Q9

CHAPTER 5 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

A set of six 120 W floodlights are left to run for 12.0 hours. The amount of energy they consume in kWh is closest to

A 0.720 kWh.

B 1.44 kWh.

C 8.64 kWh.

D 5.20×10^3 kWh.

Question 2

Consider a DC power supply that is operating at 100 V. An equivalent AC power supply would be one that

A oscillates between −100 V and +100 V.

B oscillates between 0 V and +100 V.

C oscillates between 0 V and +141 V.

D oscillates between −141 V and +141 V.

Question 3

The risk of an electrical shock **cannot** be prevented by

A reducing the voltage across the points of contact.

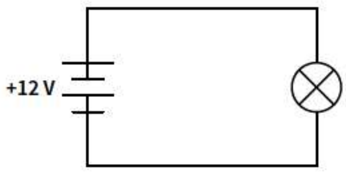
B the use of a residual current device (RCD).

C the use of an earth pin at the device socket.

D the use of a circuit breaker.

Question 4

Bel Ake is investigating the simple lamp circuit shown in the provided diagram.



She notices that the voltage drop across the lamp was initially significantly lower than she had calculated. Which one of the following factors best explains the phenomenon observed by Bel Ake?

A Internal resistance within the 12 V supply

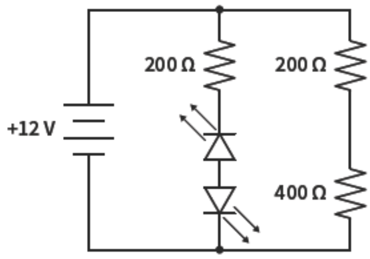
B Non-zero resistance within the connecting wires

C The 12 V supply running out of charge

D Both A and B

Question 5

Which one of the following is closest to the current flowing through the 400 Ω resistor in the provided combination circuit?



A 0 A

B 20 mA

C 30 mA

D It depends on the characteristic of the LEDs.

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (3 MARKS)

The average cost of electricity for a given household is 36 cents per kWh. In a particular week, a toaster runs for 3 hours and consumes enough electricity to cost the owner $12.50.

a Use this information to calculate the average power used by the toaster. (2 MARKS)

b Assuming the current remains constant, by what factor would the voltage across the toaster need to change in order for the weekly cost of the toaster to decrease by a factor of 4? (1 MARK)

Question 7 (6 MARKS)

Chrysanthemum is investigating safety protections against short circuits that provide a path of zero resistance between the active and neutral wires. Evaluate the effectiveness of each of the following safety devices against the risks posed by a short circuit:

a Residual current devices (RCDs) (2 MARKS)

b Circuit breakers (2 MARKS)

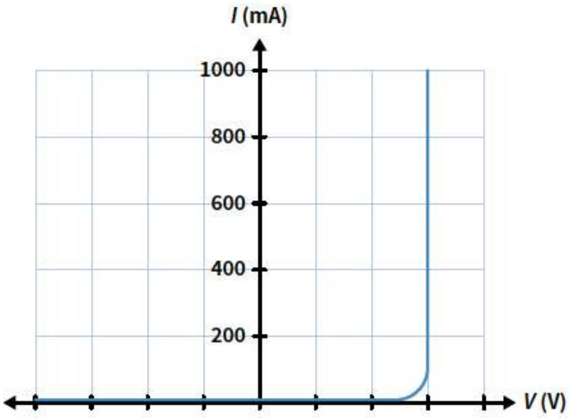
c Earth wires (2 MARKS)

Question 8 (3 MARKS)

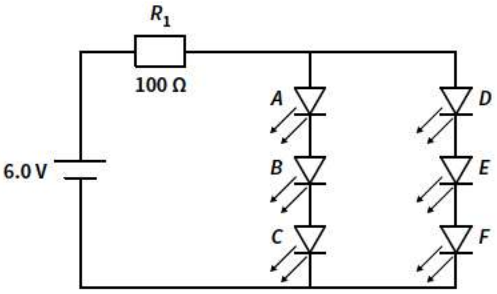
A set of Christmas lights have an equivalent resistance of 1.3 kΩ. They are connected to an AC electrical system so that the peak voltage across it is 250 V. The cost of electricity is $0.36/kWh. Use this information to calculate the cost of running the Christmas lights overnight from 8 PM to 8 AM the next morning.

Question 9 (5 MARKS)

Richard wants to make a light display using a number of identical light-emitting diodes (LEDs). The *I*-*V* graph of these diodes are shown in the included diagram.

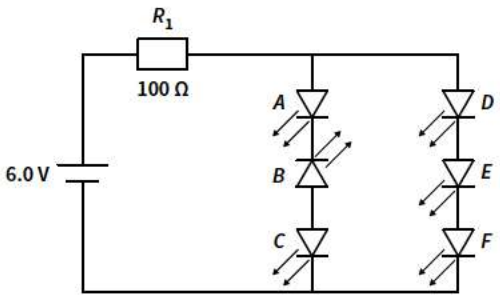


Richard sets up a circuit involving these six identical LEDs (*A*–*F*).



a What is the value of the current through R_1? (3 MARKS)

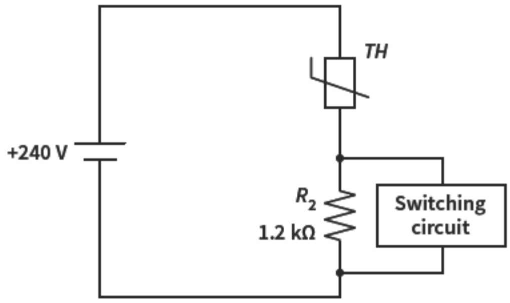
b Richard later sets up the same circuit again, but this time accidentally connects LED *B* in reverse as shown in the provided diagram. Which of the LEDs (*A*–*F*) will be on and which of the LEDs will be off? (2 MARKS)



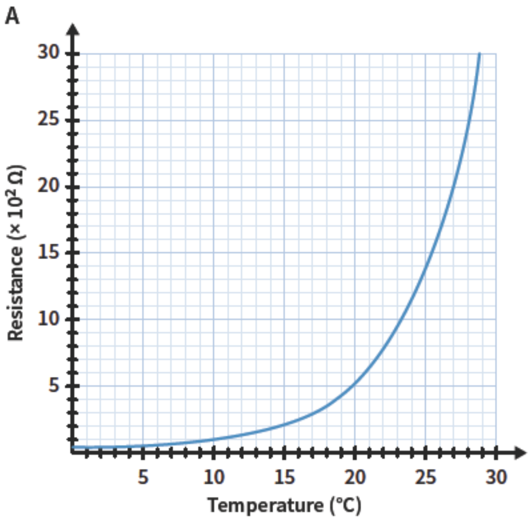
Adapted from VCAA 2009 Exam 1 Section A AoS 2 Q4–5

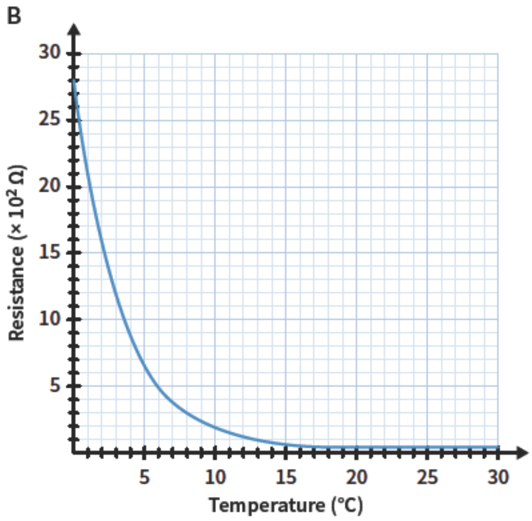
Question 10 (8 MARKS)

Shaquem, an apprentice electrician, is making a small circuit shown in the provided diagram to turn on a lighting system when the temperature rises above a certain value. To do this, he uses a thermistor (labelled *TH*). The circuit incorporates a switching circuit that turns on the lighting system when the voltage across it is greater than or equal to a threshold voltage.



a Shaquem can choose between two different thermistors to use in the circuit. They are represented by the two resistance-temperature graphs provided. However, he does not know which one describes the thermistor he should use in the circuit. Explain why B is the thermistor that he should use in this circuit. (2 MARKS)





b Shaquem wants the lighting system to first turn on when the temperature is at 10°C. Calculate the threshold voltage for the switching circuit. Assume that the switching circuit has infinite resistance. (3 MARKS)

c Shaquem uses a multimeter to determine that the resistance of the switching circuit is 2.4 kΩ. Determine the temperature of the thermistor to the nearest degree if the current flowing through the 240 V source is 200 mA. (3 MARKS)

UNIT 1, AOS 2 REVIEW

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

SECTION A

All questions in this section are worth one mark.

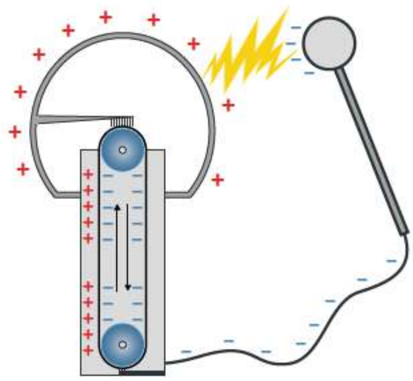
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

A Van de Graaff generator produces an electrostatic charge on a hollow metal sphere through the movement of a belt.

The belt can supply a positive charge to the dome at a rate of $500 \times 10^{-6}\ \text{C s}^{-1}$. The average energy of each coulomb of charge in the dome is 1.2 kJ.

Which one of the following is closest to the voltage across the dome after the belt has been running for 1 minute?



A 25 V

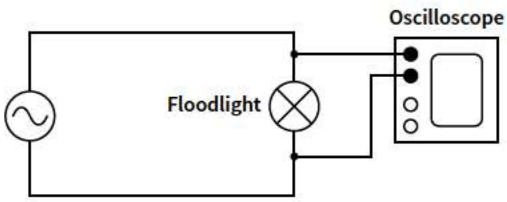
B 1.2×10^3 V

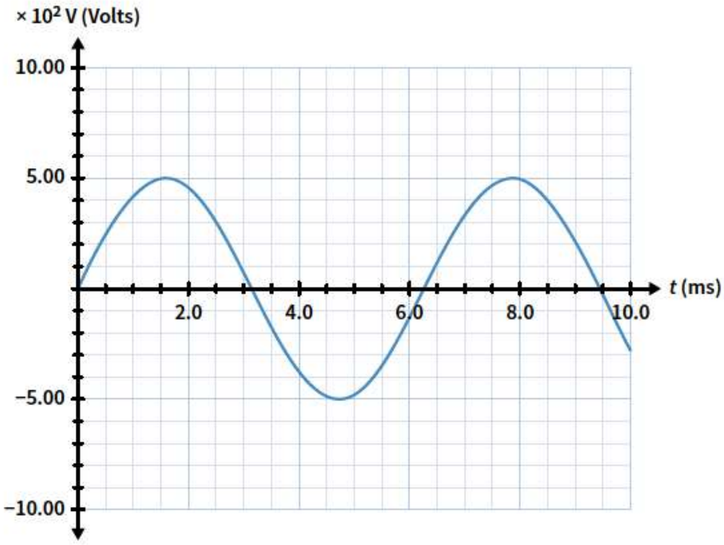
C 10 kV

D It is not possible for the voltage to be determined without further information.

Question 2

The provided diagram shows an AC supply being used to power a floodlight. An oscilloscope is attached to the circuit as shown and its output is included in the diagram.





The AC supply is to be replaced with a battery.

Which one of the following is closest to the voltage the battery would need to have for the floodlight to produce the same average brightness as it did with the AC supply?

A 250 V

B 354 V

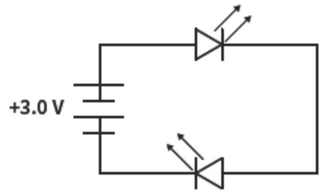
C 500 V

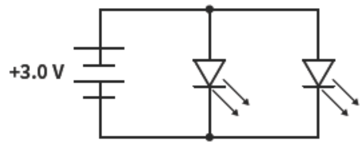
D 707 V

Adapted from 2018 VCAA Exam Section B Q4

Question 3

Consider the following two circuits each consisting of two LEDs and a 3.0 V battery. In one of the circuits, the LEDs are wired in series, and in the other, they are wired in parallel. The threshold voltage of the LEDs is 3.0 V. Assume that the LEDs will not burn out.





Which one of the following statements is true regarding the circuits?

A The LEDs will all shine with the same brightness.

B The batteries in both circuits will last for the same amount of time.

C The LEDs in series will shine brighter than the LEDs in parallel.

D The LEDs in parallel will shine brighter than the LEDs in series.

Question 4

Which one of the following statements is **incorrect** about voltmeters, ammeters and multimeters?

A A multimeter can be used to measure both current and voltage in a circuit.

B A voltmeter needs to be wired in parallel to the part of the circuit it is measuring.

C An ammeter needs to be wired in series to the part of the circuit it is measuring.

D A multimeter needs to be wired in parallel when measuring both current and voltage.

Question 5

Which one of the following statements is **incorrect** about ohmic and non-ohmic devices?

A For an ohmic device, the resistance is independent of the particular voltage or current of the circuit.

B Examples of non-ohmic devices include both thermistors and light-dependent resistors.

C A non-ohmic device is one for which we cannot use Ohm's law to calculate its current, voltage or resistance.

D The gradient at any point of an *I*–*V* graph for an ohmic device is equal to the resistance.

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (3 MARKS)

Consider two 12.0 V batteries, one of which powers a 30.0 W lamp, and the other that powers a second lamp with unknown power usage.

a How many electrons pass through the 30.0 W lamp per second? Take the magnitude of the charge of an electron as 1.6×10^{-19} C. (2 MARKS)

b It takes three times as long for the second lamp to use the same amount of energy as the 30.0 W one does. Calculate the power usage of the second lamp. (1 MARK)

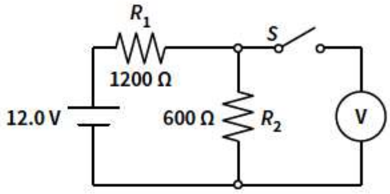
Question 7 (4 MARKS)

A small toy motor requires a potential difference of 200 mV to function. A student has taken the motor apart and is experimenting with different materials for its circuit wiring. She knows that when functioning correctly, the motor draws 0.30 A. She uses a copper alloy wire with a resistivity of $\rho = 7.8 \times 10^{-5}$ Ω m and a diameter of 6.70 mm.

What length of wire would the student need to use for the motor to function correctly?

Question 8 (6 MARKS)

Timothy constructs the circuit shown in the provided diagram. The circuit consists of a 12.0 V battery, a 1200 Ω resistor, a 600 Ω resistor and a voltmeter.



a What is the expected reading on the voltmeter when the switch *S* remains open? (1 MARK)

b Timothy closes the switch *S*. What is the voltage that should now be measured by the voltmeter? (2 MARKS)

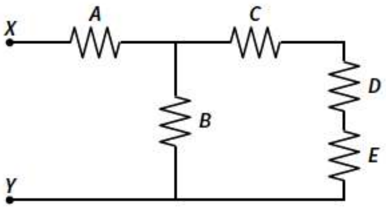
c Timothy now replaces the voltmeter with a small 170 Ω motor that requires 4.0 V across it to run. Timothy swaps the resistor R_1 for a different resistor so that the motor can function.

What should the value of the resistor replacing R_1 be so that the motor functions correctly? (3 MARKS)

Adapted from 2014 VCAA Exam Section A Q6

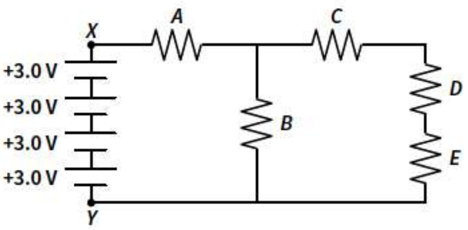
Question 9 (8 MARKS)

Five 8.00 Ω resistors are connected as shown in the provided diagram.



a Show that the total resistance of the circuit between *X* and *Y* is 14.0 Ω. (2 MARKS)

Four 3.0 V batteries are now connected in series across *XY* as shown.



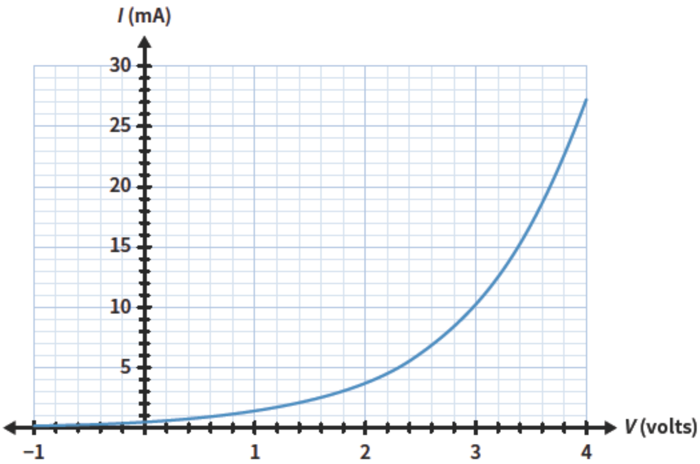
b What is the current through resistor *B*? (3 MARKS)

c What is the power dissipated in resistor *D*? (3 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 2 Q1–4

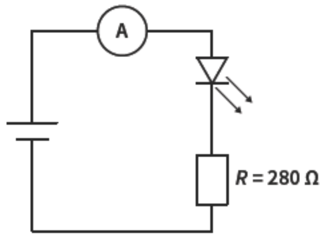
Question 10 (6 MARKS)

Carmen is experimenting with a light-emitting diode (LED). The LED's characteristics are shown in the provided diagram.



a Based on the *I*-*V* graph, what type of device (ohmic or non-ohmic) is the LED? (1 MARK)

Carmen connects the LED to a circuit as shown in the provided diagram.



b The current measured by the ammeter is 15 mA.
Determine the voltage of the battery. (3 MARKS)

c State the type of energy transformation occurring in the LED and the type of energy transformation occurring in the resistor. (2 MARKS)

Adapted from 2013 VCAA Exam Section A Q12

Question 11 (5 MARKS)

A family has moved into a new home and are having difficulties with the household electricity.

a All the appliances in the house are wired in series with one another. Give two reasons for why this is a bad idea. (2 MARKS)

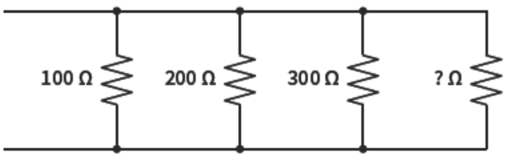
b The family has noticed that the mains plugs for some old outdoor appliances only have two pins and no double insulation, however they do not think this is a danger since the appliances draw a fairly low voltage. The family continues using the appliances outside, even when they are wet from the rain. Explain why the use of such appliances in these conditions poses significant safety hazards. (3 MARKS)

Question 12 (6 MARKS)

A student needs an electric circuit they are designing to have a resistance of 200 Ω. However, he only has five 600 Ω resistors that he can use.

a Sketch how he could connect some or all of the resistors to create a total resistance of 200 Ω. (3 MARKS)

The student wants to create an overall resistance of 75 Ω, and does this by putting four resistors in parallel as shown. One of the resistor's values is unknown.



b Explain whether it is possible for the equivalent resistance of this circuit to be 75 Ω. Include any necessary calculations. (3 MARKS)

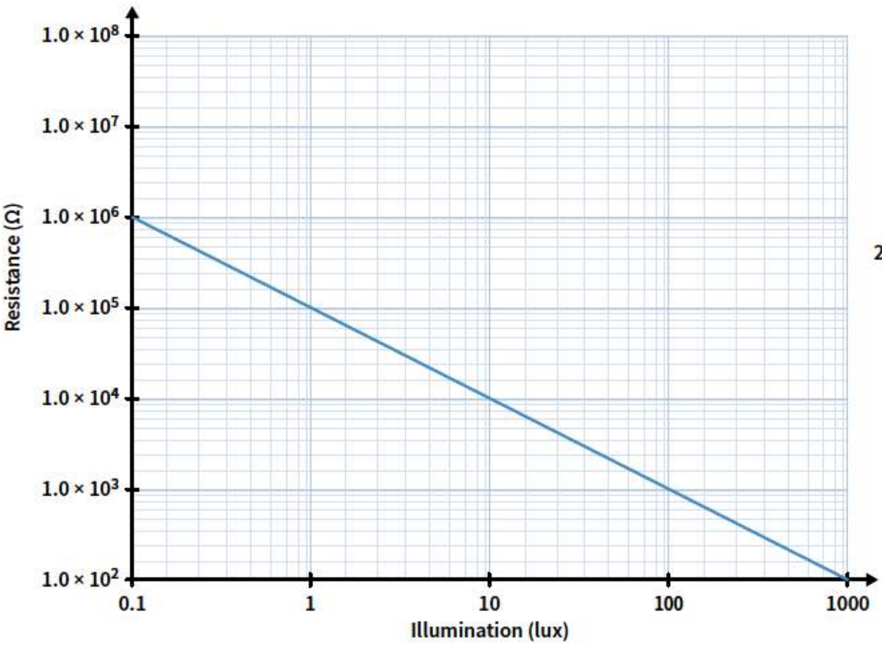
Adapted from 2013 VCAA Exam Section A Q10

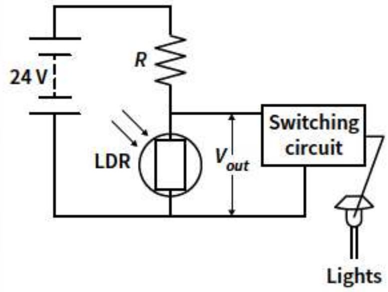
Question 13 (7 MARKS)

Randall wants to install some garden lights that will come on at sunset. A circuit will be used to control the lights; it consists of

- a 24.0 V DC power source,
- a light-dependent resistor (LDR),
- a resistor *R*,
- and a switching circuit (an internal circuit that turns the lights on or off).

The resistance-illumination graph of the LDR and the setup of the circuit are shown in the provided diagrams.





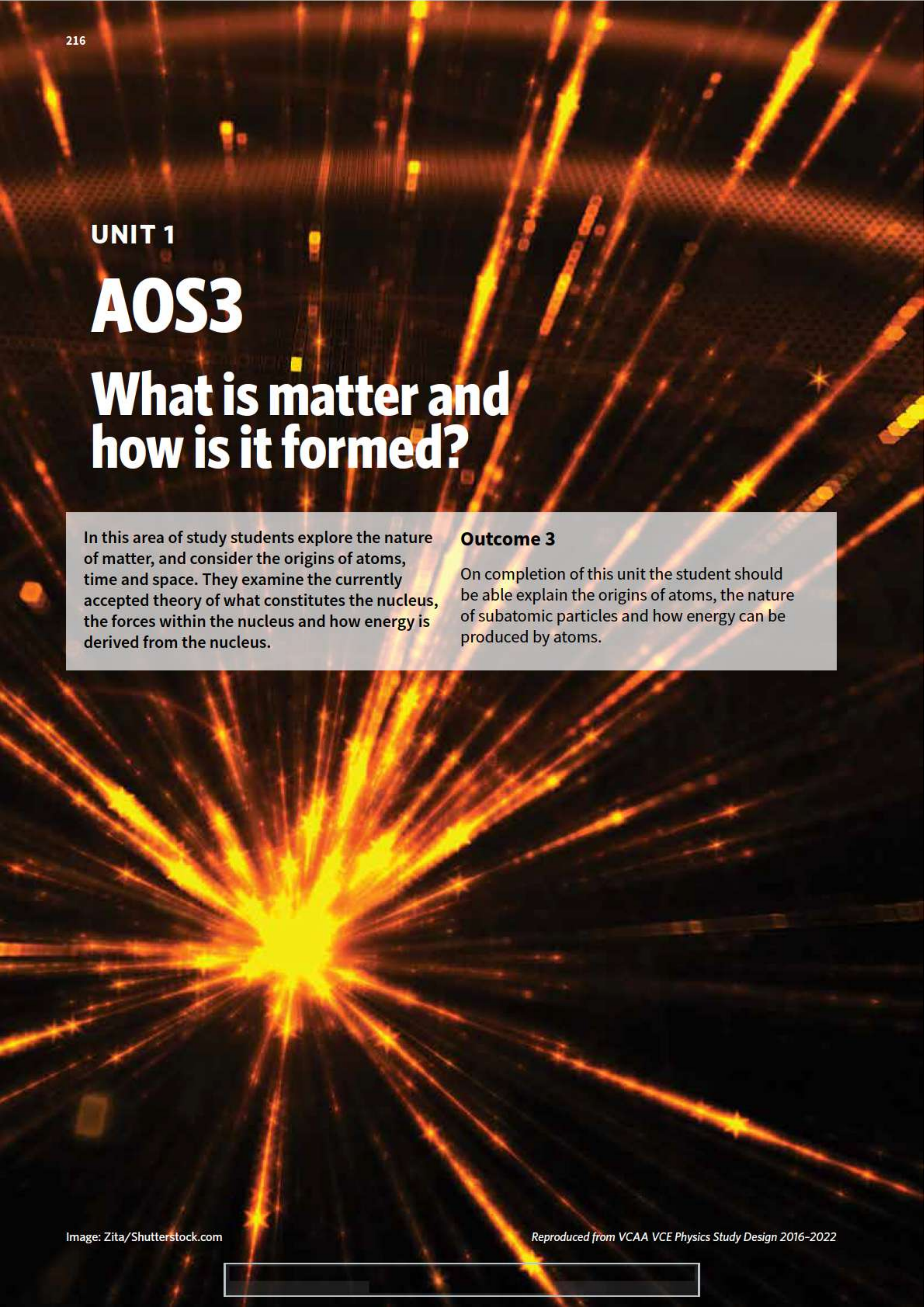
a The switching circuit turns the lights on when V_{out} is 6.0 volts. Randall wants the lights to come on when the illumination has fallen to 10 lux.

What must the value of the resistor *R* be in the circuit to ensure the lights come on at 10 lux? (3 MARKS)

b As sunset approaches, and the daylight decreases, does the value of V_{out} increase or decrease? Justify your answer. (2 MARKS)

c Randall decides that he wants the lights to come on later (when there is less daylight). Should he increase or decrease the resistance *R* to achieve this? Explain your answer. (2 MARKS)

Adapted from 2010 VCAA Exam 1 Section A AoS 2 Q6–8



UNIT 1

AOS3

What is matter and how is it formed?

In this area of study students explore the nature of matter, and consider the origins of atoms, time and space. They examine the currently accepted theory of what constitutes the nucleus, the forces within the nucleus and how energy is derived from the nucleus.

Outcome 3

On completion of this unit the student should be able explain the origins of atoms, the nature of subatomic particles and how energy can be produced by atoms.

Image: Zita/Shutterstock.com

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UNIT 1 AOS 3, CHAPTER 6

Particles in the nucleus

06

Key knowledge

- explain nuclear stability with reference to the forces that operate over very small distances
- describe the radioactive decay of unstable nuclei with reference to half-life
- model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives
- apply a simple particle model of the atomic nucleus to explain the origin of α, $\beta-$, $\beta+$ and γ radiation, including changes to the number of nucleons
- explain nuclear transformations using decay equations involving α, $\beta-$, $\beta+$ and γ radiation
- analyse decay series diagrams with reference to type of decay and stability of isotopes
- relate predictions to the subsequent discoveries of the neutron, neutrino, positron and Higgs boson
- describe quarks as components of subatomic particles
- distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force
- compare the nature of leptons, hadrons, mesons and baryons
- explain that for every elementary matter particle there exists an antimatter particle of equal mass and opposite charge, and that if a particle and its antiparticle come into contact they will annihilate each other to create radiation.

Image: Monet_3k/Shutterstock.com

6A THE STANDARD MODEL

All matter is made up of atoms, which are themselves made up of protons, neutrons and electrons. Have you ever wondered if protons and neutrons were made up of something smaller? The Standard Model is our current theory of fundamental particles at the subatomic scale.

6A The Standard Model	6B Nuclear stability and the fundamental forces	6C Radioactive half-life	6D Types of nuclear radiation

Study design dot points

- relate predictions to the subsequent discoveries of the neutron, neutrino, positron and Higgs boson
- describe quarks as components of subatomic particles
- compare the nature of leptons, hadrons, mesons and baryons
- explain that for every elementary matter particle there exists an antimatter particle of equal mass and opposite charge, and that if a particle and its antiparticle come into contact they will annihilate each other to create radiation

Key knowledge units

Quarks	1.3.13.1
Leptons, hadrons, mesons, and baryons	1.3.15.1
Antimatter	1.3.16.1
Particle discoveries	1.3.12.1

No previous or new formulas for this lesson

Definitions for this lesson

antiparticle a particle with the same mass and spin as its corresponding particle but with opposite charge and other quantum numbers (such as baryon number, lepton number, and strangeness)

baryon a subatomic particle made up of an odd number of quarks (typically 3), such as a proton or a neutron

composite particle a particle that is composed of two or more elementary particles

elementary particle a particle that is not made up of other particles

hadron a subatomic particle made up of two or more quarks held together by the strong force

meson a subatomic particle made up of one quark and one antiquark

nucleon a proton or a neutron

quarks elementary particles that can combine to form hadrons

radiation any type of energy, or energy-carrying particles, that spreads as it travels away from a source

Quarks 1.3.13.1

OVERVIEW

Protons and neutrons are each composed of three quarks. Quarks are elementary particles, meaning they are not composed of particles and cannot be broken down.

THEORY DETAILS

Particles in an atom

All matter is composed of atoms. Atoms are the smallest constituent of matter that can still be considered an element. For example, if we take a lump of gold and continue breaking it into pieces, the smallest piece of gold we could have would be one atom of gold.

Inside of an atom, there are several kinds of subatomic particles:

- The centre of an atom is called the nucleus.
  - Made up of positively charged protons (charge = $+e$, where e is the elementary charge equal to 1.60×10^{-19} C) and neutral neutrons (charge = 0).
  - Together, protons and neutrons are called nucleons.
- Around the nucleus are negatively charged particles called electrons which occupy different energy levels.
  - Electrons have a charge of $-e$.
  - Electrons are elementary particles, which means they cannot be divided into smaller constituent particles.
  - Electrons are approximately 2000 times smaller than nucleons.

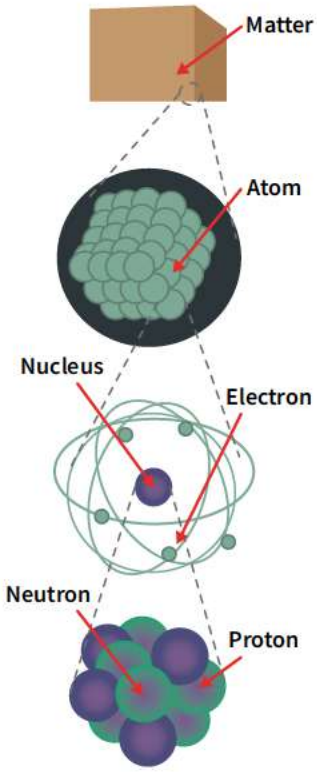


Figure 1 Matter is made of atoms. Atoms are composed of a nucleus and electrons. The nucleus is composed of nucleons (protons and neutrons).

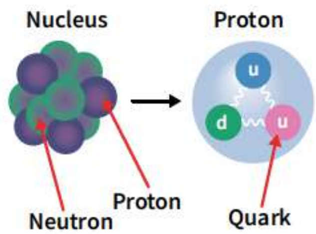


Figure 2 Protons and neutrons are composite particles that are each made up of three quarks.

Quarks

Physicists Murray Gell-Mann and Georg Zweig independently proposed in 1964 that nucleons were not elementary particles, and were instead composed of elementary particles called quarks. Experimental evidence for the existence of six types (called 'flavours') of quarks was found by 1995.

Table 1 Symbols and charges of the quarks

Quark Flavour	Up	Down	Charm	Strange	Top	Bottom
Symbol	u	d	c	s	t	b
Charge	$+\frac{2}{3}e$	$-\frac{1}{3}e$	$+\frac{2}{3}e$	$-\frac{1}{3}e$	$+\frac{2}{3}e$	$-\frac{1}{3}e$
Mass (MeV c^{-2})	2.2	4.7	1280	96	172 760	4180

The six quarks are divided into three generations:

- First generation: the up and down quarks
- Second generation: the strange and charm quarks
- Third generation: the bottom and top quarks

Each quark also has a corresponding antiquark. The properties of such antiparticles will be explored in more detail in the antimatter section.

The higher-generation quarks are heavier and unstable, and as a result they quickly decay into up and down quarks. Second and third generation quarks can only be produced in high-energy collisions like those of cosmic rays or in particle accelerators (like the Large Hadron Collider at CERN).

Leptons, hadrons, mesons, and baryons 1.3.15.1

OVERVIEW

The Standard Model describes three categories of elementary particles: quarks, leptons, and bosons. Quarks can combine to form composite particles called baryons or mesons (which together are called hadrons).

THEORY DETAILS

The Standard Model

The Standard Model is the main theory of particle physics. It classifies all known elementary particles and helps explain three of the four fundamental forces (the electromagnetic force, the strong force, and the weak force), which are explored further in Lesson 6B.

It categorises the elementary particles that act as the building blocks of matter into two categories – **quarks and leptons**. It also describes particles called **bosons**. Bosons can be considered the "carriers" of the fundamental forces – particles exert the forces on each other by exchanging bosons.

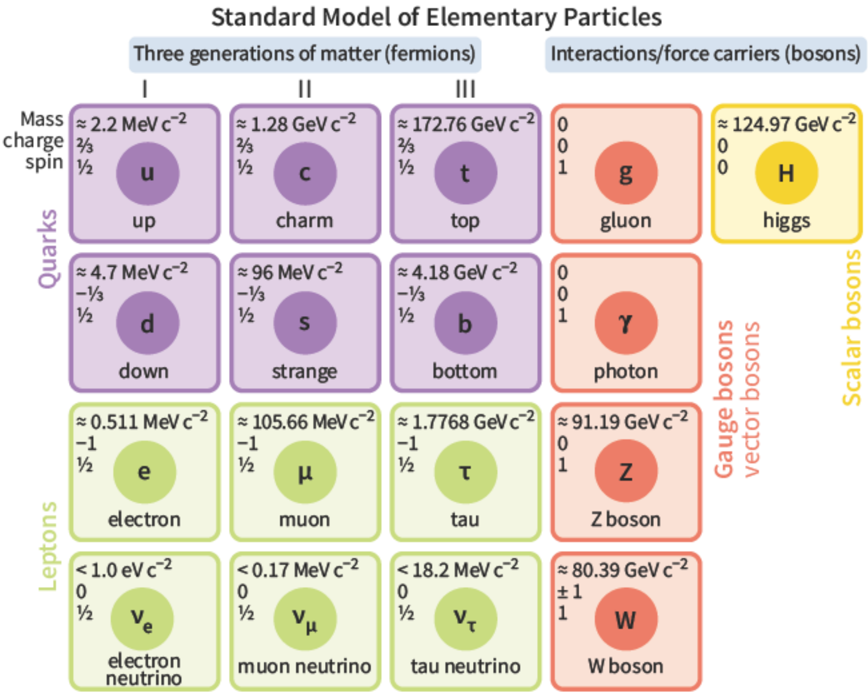


Figure 3 The Standard Model

Hadrons

A hadron is a subatomic particle composed of two or more quarks. Hadrons are split into two sub-categories: baryons and mesons.

Baryons

Baryons are composite particles composed of an odd number of quarks (typically 3). As shown earlier in the section on quarks, protons and neutrons are baryons as they are each composed of three quarks.

A proton is a baryon composed of **two** up quarks and **one** down quark, written as uud. A neutron is composed of **one** up quark and **two** down quarks, written as udd. Examples of other baryons include the Σ^+ particle (uus), Ξ^- particle (dss) and Ω^- particle (sss).

When examining a particle composed of quarks, the sum of the charges of the quarks is the charge of the resulting particle. This is why protons have a charge of +*e* and neutrons have 0 charge, as shown in Figure 4.

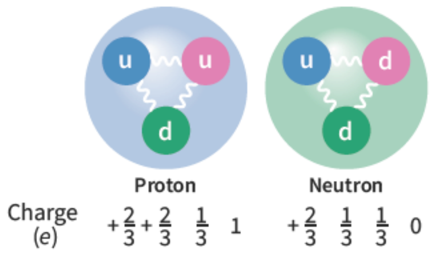


Figure 4 The charges of the quarks that make up protons and neutrons add up to give their respective total charges.

Mesons

Mesons are composite particles composed of a quark and an antiquark. All mesons are unstable, with the longest-living mesons having a mean lifetime of approximately 10^{-8} s.

An example of a meson is the positive pion, which is made of one up quark and one down antiquark ($u\overline{d}$). Its antiparticle is the negative pion, which is made of one up antiquark and one down quark ($\overline{u}d$). The positive pion and the negative pion are shown in Figure 5.

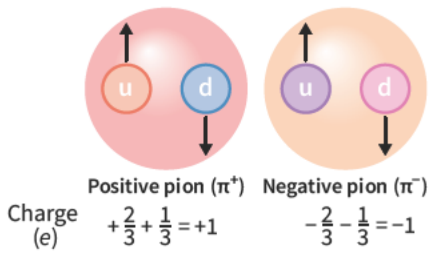


Figure 5 The charges of the quarks that make up mesons sum to give their respective total charges.

Leptons

Leptons are another category of elementary particles. Electrons fall into this category. Leptons are divided into three generations:

- First generation: the electron (e^-) and the electron neutrino (ν_e)
- Second generation: the muon (μ^-) and the muon neutrino (ν_μ)
- Third generation: the tau particle (τ) and the tau neutrino (ν_τ)

The muon and tau particles are bigger and less stable than the electron, and will quickly decay into electrons and neutrinos. Neutrinos are very small neutrally charged particles, they are created in various decay processes and very rarely interact with matter.

When 'neutrino' or 'antineutrino' is mentioned in the context of a decay process in this book, this refers to electron neutrinos and antielectron neutrinos.

Bosons

Bosons are particles that do not make up matter. The elementary bosons considered in the standard model are the gauge bosons (the gluon, photon, Z boson, and W bosons) and the Higgs boson. The gauge bosons are each associated with a fundamental force:

Table 2 Gauge bosons and their associated fundamental forces

Gauge boson	Fundamental Force
Gluon	Strong force
Photon	Electromagnetic force
Z boson and W boson	Weak force

- The photon is the particle that makes up light. The concept of light acting like both waves and particles will be explored in detail in VCE Physics Units 3 & 4.
- The 'graviton' is the hypothesised gauge boson associated with gravity, which has not (yet) been proven to exist.

The detailed ways in which these bosons are associated with the fundamental forces is beyond the scope of VCE Physics.

The Higgs boson is a particle that interacts with the Higgs field. Interactions of particles with the Higgs field and the Higgs boson are responsible for particles having mass.

Quantum numbers

In a physical interaction, certain quantities follow conservation laws. Common examples in classical physics include conservation of momentum or conservation of energy (which also apply at subatomic scales!)

Quantum numbers are used to describe qualities that are conserved during quantum interactions. A familiar example of a quantum number is charge. The total charge of all particles before an interaction (such as a collision) is equal to the total charge after the interaction.

Another important quantum number is called 'spin'.

- Spin is a concept used to explain the intrinsic angular momentum of particles, but the particles are not actually spinning.
  - This is an example of how weird physics becomes at subatomic scales!
- It is called 'spin' because the mathematics used to describe this property is similar to that used to describe classical angular momentum.
- All quarks and leptons have a spin of ½.
  - Particles with 'half-integer' spin are called fermions. Fermions are the key building blocks of matter.
  - All particles that are not fermions are bosons (they have 'integer' spin).
  - Further details of spin are outside the scope of this course.

Certain quantum numbers are specific to the identity of a particle:

Baryon number

- All baryons have a quantum number called the baryon number ($B = 1$).
- The baryon number of a particle is the sum of the baryon numbers of its quarks and antiquarks.
- All particles that are not baryons have a baryon number of 0.

Table 3 Baryon numbers of particles

	Quark	Antiquark	Baryon	Mesons, leptons, and bosons
Baryon number (B)	$+\frac{1}{3}$	$-\frac{1}{3}$	+1	0

Lepton number

- All leptons have a quantum number called the lepton number ($L = 1$).
- It is useful to analyse interactions of leptons with generational quantum numbers. These are the electronic lepton number (L_e), muonic lepton number (L_μ), and tauonic lepton number (L_τ).
- The corresponding antiparticles have negative generational lepton numbers.
- All particles that are not leptons have a lepton number of 0.

Table 4 Generational lepton numbers of the different leptons

	L_e	L_μ	L_τ
e^- and ν_e	+1	0	0
μ^- and ν_μ	0	+1	0
τ and ν_τ	0	0	+1

Quark flavour quantum numbers

- The heavier quarks each have a quantum number that corresponds to their flavour (charm, strangeness, topness, and bottomness). We will only focus on the first of these to be identified, strangeness.
- The strangeness of a particle is the sum of the strangeness of its quarks.
- Quark flavour quantum numbers are only conserved in interactions that do not involve the weak force.

Table 5 Strangeness of quarks

	Strange quark	Antistrange quark	Other quarks or antiquarks
Strangeness (S)	−1	+1	0

Worked example 1

Consider the Xi baryon Ξ^0(uss).

a Calculate the charge of Ξ^0.

b Calculate the baryon number of Ξ^0.

c Calculate the strangeness of Ξ^0.

Working	Process of thinking
a Charges: $u = \frac{2}{3}e, s = -\frac{1}{3}e$	u refers to an up quark and s to a strange quark
Charge $= \left(\frac{2}{3} - \frac{1}{3} - \frac{1}{3}\right)e = 0e = 0$	We sum the charges of each quark to get the total charge.
b Baryon numbers: $u = +\frac{1}{3}$, $s = +\frac{1}{3}$	
$B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$	We sum the baryon numbers of each quark to get the baryon number.
c Strangeness: $u = 0, s = -1$	
$S = 0 - 1 - 1 = -2$	We sum the strangeness of each quark to get the strangeness.

Antimatter 1.3.16.1

OVERVIEW

Every particle has a corresponding antiparticle. When a particle and its corresponding antiparticle collide, they annihilate.

THEORY DETAILS

An antiparticle has the same mass and spin as their corresponding particle, but has an opposite value for the charge and other quantum numbers covered in the previous section. An antiparticle may have the same momentum and energy as its corresponding particle. An example of an antiparticle is the positron (e^+), which is the antiparticle of the electron (e^-).

Most antiparticles are designated by a horizontal line above the symbol of their corresponding particle. For example, the antistrange quark is written as $\bar{s}$.

For a particle to be its own antiparticle, all the quantum numbers must be 0. For example, the photon is its own antiparticle.

A particle and an antiparticle can be produced through a process called **pair production**. For example, the energy of a photon can be converted into an electron and positron: $\gamma \rightarrow e^- + e^+$. This process needs to occur near a nucleus (so that momentum is conserved).

When a particle and its antiparticle collide, they **annihilate** and release energy in the form of light or other particles. For example, an electron and a positron annihilate to produce photons (light): $e^- + e^+ \rightarrow \gamma + \gamma$.

Worked example 2

Consider the Kaon $K^+(u\bar{s})$.

a Calculate the charge of K^+.

b Calculate the baryon number of K^+.

c Calculate the strangeness of K^+.

Working	Process of thinking
a Charges: $u = \frac{2}{3}e, \bar{s} = \frac{1}{3}e$	u refers to an up quark and $\bar{s}$ to an antistrange quark. The charge for $\bar{s}$ is the opposite of the charge of a strange quark.
Charge $= \left(\frac{2}{3} + \frac{1}{3}\right)e = 1e$	We sum the charges of each quark to get the total charge.
b Baryon numbers: $u = +\frac{1}{3}, \bar{s} = -\frac{1}{3}$	
$B = \frac{1}{3} - \frac{1}{3} = 0$	We sum the baryon numbers of each quark to get the baryon number.
c Strangeness: $u = 0, \bar{s} = +1$	
$S = 0 + 1 = 1$	We sum the strangeness of each quark to get the strangeness.

Particle discoveries 1.3.12.1

OVERVIEW

The discoveries of the neutron, neutrino, positron, and Higgs boson all went through phases of theoretical prediction followed by experimental discovery.

THEORY DETAILS

Neutron

Prediction:

- In the early 20th century, physicists knew that the atomic mass of nuclei was greater than its atomic number and that most of the mass was concentrated in the centre of the atom.

- Initially, physicists thought that there were both protons and electrons in the nucleus, so that extra protons in the nucleus could add the required mass and have their charge 'cancelled out' by the presence of electrons.
- This theory does not align with spin predictions and other quantum mechanical theories.

Discovery:

- A 1930 experiment by Walther Bothe and Herbert Becker found that alpha particles (described in Lesson 6D) hitting a beryllium atom produced uncharged radiation. They thought the radiation might be gamma radiation, but this did not align with the experimental results.
- Based on this experiment, in 1932 James Chadwick performed a series of experiments that demonstrated that the uncharged radiation was actually uncharged particles with approximately the same mass as a proton – these were neutrons! He won the 1935 Nobel Prize in Physics for his discovery.

Neutrino

Prediction:

- Wolfgang Pauli proposed the existence of the neutrino in 1930 because an extra unobserved particle was needed in order for the experimentally observed results of beta decay (described in Lesson 6D) to follow momentum conservation and energy conservation.

Discovery:

- In 1956, Clyde Cowan and Frederick Reines ran an experiment where an unknown type of particle produced by a nuclear reactor reacted with protons. By observing the products of the reaction, they were able to prove that the unknown particles had to be antineutrinos. Scientists knew this meant that neutrinos must exist too.

Positron

Prediction:

- In 1928, Paul Dirac published a paper that predicted that electrons could have positive and negative charges as a mathematical consequence of his calculations. He then proposed the positron as a separate particle in 1931 as a response to the controversy surrounding his prediction.

Discovery:

- In 1932, Carl David Anderson ran an experiment where cosmic rays passed through a cloud chamber (a container full of a gas that leaves cloud-like tracks where energetic charged particles passed through). An external magnetic field was applied to the cloud chamber so charged particles would have their path bent by the magnetic force. Anderson discovered the positron by observing a particle that had the same mass to charge ratio as an electron, but with a positive charge (indicated by the direction in which its path was bent), as shown in Figure 6.

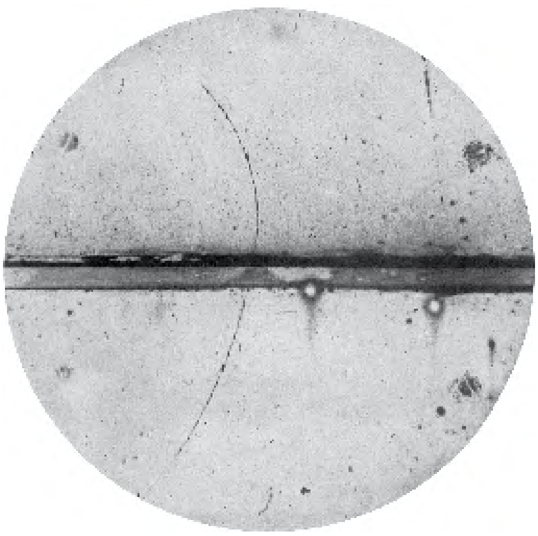


Figure 6 The image created by Anderson that proved the existence of the positron. The positron travelled from the bottom to the top of the image, curving to the left. An electron under the same conditions would curve to the right.

Higgs boson

Prediction:

- Initially, the Standard Model predicted that the gauge bosons of the electromagnetic force and weak force should be massless. This holds for the photon, but the W and Z bosons are massive, even more massive than an atom of iron!
- In 1964, Peter Higgs predicted that there must be another particle (and associated field) that particles were interacting with that was responsible for producing their mass. This would be allowed by the Standard Model, while matching the experimental observation of the mass of the W and Z bosons.

Discovery:

- The discovery of the Higgs boson was announced on July 4, 2012 by the team at the ATLAS and CMS detectors at the Large Hadron Collider at CERN. Protons were collided together trillions of times at speeds close to the speed of light. By analysing promising collisions and with statistical analysis physicists proved the existence of the particle.

Theory summary

- The standard model divides the fundamental particles into three categories – quarks, leptons and bosons.
  - Quarks combine to form baryons (composed of an odd number of quarks) and mesons (composed of a quark and antiquark).
  - Leptons are composed of the electron, muon and tau particle and their corresponding neutrinos.
  - Gauge bosons are responsible for the fundamental forces. The Higgs boson and Higgs field are responsible for particles having mass.
- All particles have an antiparticle that has the same mass and spin but opposite charge and other quantum numbers (such as baryon number, lepton number, and strangeness).
  - Some particles are their own antiparticle (e.g. photons).
  - A particle and an antiparticle can annihilate to produce energy/particles (e.g. photons).
  - A particle and an antiparticle can be produced through pair production if they are near a nucleus (to ensure momentum conservation).
- Particles have different properties like mass, charge, spin, strangeness, baryon number, and lepton number.
  - Some of these properties follow conservation laws (meaning they cannot change in the process of a reaction) while others (like mass) do not.
- All fundamental particles went through a process of prediction and then discovery. The nature of these predictions and the subsequent experimental discovery varies in each case.

KEEN TO INVESTIGATE?

CERN: The Higgs Boson
home.cern/science/physics/higgs-boson

Symmetry: Ten Things You Might Not Know About Antimatter
symmetrymagazine.org/article/april-2015/ten-things-you-might-not-know-about-antimatter

YouTube video: Physics Girl – Quarks Explained in Four Minutes
youtu.be/LraNu_78sCw

YouTube video: SciShow – How Quarks Fixed the Mess That Was Particle Physics
youtu.be/j-993mWNcHk

CONCEPT DISCUSSION QUESTION

Antimatter is a concept often fantastically exaggerated in science fiction. It is easy to see why: only a gram of antimatter (10^{-2} kg) could produce an explosion the size of a nuclear bomb. In movies like *Angels and Demons* (2009), antimatter stolen from CERN threatens to destroy the world.

In reality, the amount of antimatter created at CERN in total is about 1 nanogram (10^{-12} kg). CERN has been successful in creating antihydrogen. Antimatter created at CERN has to be stored in isolation from all other matter. This requires the use of a vacuum chamber, electric fields and magnetic fields. To detect the created antimatter, scientists turn off these systems so that the antimatter collides with the walls of the detector.

Discuss whether antimatter poses the existential threat that it seems to in science fiction with reference to the experiments at CERN.

Answers on page 506

Hints
What are some examples of antiparticles? Are these all rare?
What happens when a particle and its antiparticle collide?
What are the components of an antihydrogen atom?
Is it easy to store antimatter for long periods of time? Is it cost-efficient?

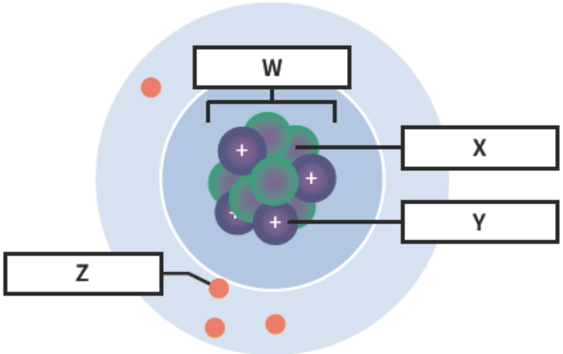
6A Questions

THEORY REVIEW QUESTIONS

Question 1

Select an appropriate word from the word bank for each letter in the diagram. Use each word once.

- Electron
- Neutron
- Proton
- Nucleus



Question 2

Copy the table and for each particle, place a tick to indicate whether it is an elementary or composite particle.

		Elementary	Composite
a	Electron		
b	Proton		
c	Up quark		
d	Pion		
e	Higgs boson		
f	Tau neutrino		
g	Strange antiquark		
h	Hydrogen atom		
i	Photon		
j	Positron		

Question 3

Write down the name of each of the following particles and categorise each particle as either a quark, lepton, or boson.

a u

b τ

c ν_μ

d $\bar{b}$

e Z

f e^-

g e^+

h c

i μ

j γ

Question 4

Read the following statements and state whether they are true or false.

a The antineutrino was directly observed during its discovery.

b The positron was directly observed during its discovery.

c The existence of particles can be predicted by looking for inconsistencies in the Standard Model.

d New particles have always been discovered within a decade after they were predicted.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 5 (4 MARKS)

The process of beta decay was mentioned in this lesson when describing Pauli's prediction of the neutrino. The process of beta decay will be discussed in detail in Lesson 6D. The reaction in beta decay (a neutron decaying into a proton, electron, and antineutrino) can be written as:

$n \rightarrow p + e^- + \bar{\nu}$

Do not worry about the reaction notation used in this question – it is designed to introduce the key takeaways of the Standard Model that will be relevant in later lessons.

One of the most important concepts in particle physics is 'conservation laws'. These describe certain properties of a system that do not change when a physical process or interaction (like beta decay) takes place.

Prompts

a What is the baryon number and electronic lepton number (L_e) of the neutron?

	Baryon number (B)	Lepton number (L_e)
A	1	1
B	⅓	0
C	0	1
D	1	0

b What are the baryon numbers of the proton, electron, and antineutrino?

	Proton	Electron	Antineutrino
A	1	–1	0
B	1	0	0
C	0	–1	1
D	1	1	0

c What are the electronic lepton numbers (L_e) of the proton, electron, and antineutrino?

	Proton	Electron	Antineutrino
A	0	–1	–1
B	1	1	1
C	0	–1	1
D	0	1	–1

d Calculate the sum of the baryon numbers before the decay and after the decay. Identify the relationship between these two numbers.

e Calculate the sum of the electronic numbers before the decay and after the decay. Identify the relationship between these two numbers.

Question

f In physics, quantities often have to be conserved throughout an interaction. List four different laws of conservation demonstrated in beta decay. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 6 (2 MARKS)

Explain how the positron was experimentally discovered.

Question 7 (3 MARKS)

Describe the Standard Model in terms of the three main categories of elementary particles, briefly explaining which particles make up each category.

Question 8 (2 MARKS)

The antiparticle of a baryon is composed of the antiquarks of each respective quark in the baryon.

Consider the proton (uud).

a Write down the quark structure of the antiproton. (1 MARK)

b Verify that the antiproton has the correct charge. (1 MARK)

Question 9 (8 MARKS)

Calculate the baryon number of the following particles and hence classify them as baryons or mesons.

a Ω^- (sss) (2 MARKS)

b K^0 (d$\bar{s}$) (2 MARKS)

c The rare pentaquark P_c^+ (uudc$\bar{c}$) (2 MARKS)

d Ξ^-(dss) (2 MARKS)

Question 10 (4 MARKS)

Calculate the strangeness of the following particles.

a Ω^- (sss) (1 MARK)

b K^0 (d$\bar{s}$) (1 MARK)

c The rare pentaquark P_c^+ (uudc$\bar{c}$) (1 MARK)

d Ξ^-(dss) (1 MARK)

Question 11 (2 MARKS)

Describe the differences in the compositions of baryons and mesons.

Question 12 (4 MARKS)

If a particle is its own antiparticle, the quantum numbers of the particle and the antiparticle are equal.

a Is the neutron its own antiparticle? Justify your answer with reference to baryon number. (2 MARKS)

b Is the neutral pion π^0 (u$\bar{u}$) its own antiparticle? Explain your answer. (2 MARKS)

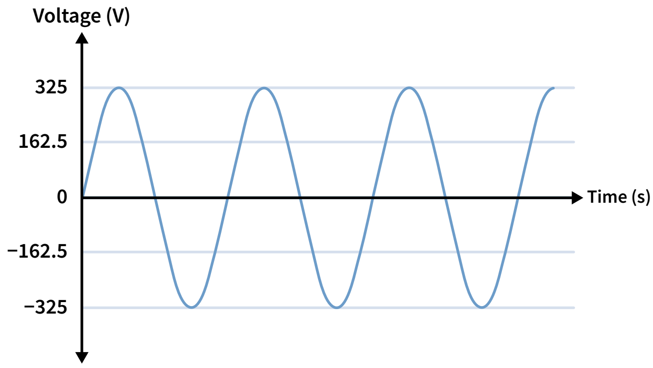
Previous lessons

Question 13 (3 MARKS)

Explain why increasing the Earth's average albedo would reduce the greenhouse effect.

Question 14 (2 MARKS)

Determine the RMS voltage of this AC voltage signal.



Key science skills

Question 15 (3 MARKS)

While the neutron was discovered by James Chadwick in 1932, it was first predicted in the early 1900s.

The four steps in the scientific method identified in Chapter 1 are: 'observe and question', 'formulate a hypothesis', 'experiment', and 'analyse and conclude'.

a Identify the part of the scientific method that best describes the initial prediction that there were both protons and electrons in the nucleus. (1 MARK)

b With reference to the scientific method, explain why it is important that Chadwick performed a series of experiments in his discovery of the neutron and repeated each of those experiments multiple times. (2 MARKS)

6B NUCLEAR STABILITY AND THE FUNDAMENTAL FORCES

Lesson 6A introduced us to the concept of subatomic particles such as protons and neutrons which are made of quarks. How can the nucleus of an atom stay together when the positively charged protons repel each other? This lesson introduces the fundamental forces and examines how the careful balance between forces within the nucleus determines its stability.

6A The Standard Model	6B Nuclear stability and the fundamental forces	6C Radioactive half-life	6D Types of nuclear radiation

Study design dot points

- explain nuclear stability with reference to the forces that operate over very small distances
- distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force

Key knowledge units

The strong and weak nuclear forces	1.3.14.1
Nuclear stability	1.3.6.1

No previous or new formulas for this lesson

Definitions for this lesson

fundamental forces the four forces that cannot be broken down into other forces: the gravitational force, the electromagnetic force, the strong force, and the weak force

isotope an atom of an element that has the same number of protons but a different number of neutrons compared to another atom of the element

nucleon a proton or a neutron

radioactive decay the process of an atom becoming more stable by losing energy and emitting particles or photons

radioisotope an isotope that will undergo radioactive decay

strong force the fundamental force that holds quarks together to form nucleons and that holds nucleons together within the nucleus

weak force the fundamental force responsible for beta decay by changing the flavour of a quark

The strong and weak nuclear forces 1.3.14.1

OVERVIEW

All forces can be reduced to the four fundamental forces. The fundamental forces most relevant to the nucleus are the strong force, the weak force, and the electromagnetic force.

THEORY DETAILS

Fundamental forces

There are four fundamental forces: the gravitational force, the electromagnetic force, the strong nuclear force and the weak nuclear force. The word 'fundamental' means that, in our current scientific understanding, they cannot be further broken down into a simpler process.

While the gravitational force and the electromagnetic force can be easily observed in everyday life, the strong and weak forces only operate on sub-atomic scales. The gravitational force is so weak in comparison to the other fundamental forces that it is negligible at sub-atomic distances.

Table 1 The four fundamental forces vary in their approximate relative strength, range, and the particles that experience the force.

Force	Relative strength (approximate)	Range	Particles that experience the force
Gravity	1 (weakest)	∞	All particles with mass
Electromagnetic	10^{36}	∞	Electrically charged particles
Strong	10^{38} (strongest)	~10^{-15} m (size of a quark)	Quarks and nucleons
Weak	10^{25}	~10^{-18} m	Quarks and leptons

Strong force

The strong force holds together quarks within a proton or neutron and holds together the nucleons in the nucleus.

- At very short distances the strong force is very repulsive. This stops protons and neutrons from overlapping. The repulsive aspects of the strong force can be imagined like compression springs keeping each nucleon at least a minimum distance apart from each other.
- The strong force is strongly attractive at a slightly larger distance. This can be imagined like a rubber band holding the nucleus together.

The effect of keeping the nucleus held together is a residual effect of the strong force acting between the quarks within protons and neutrons.

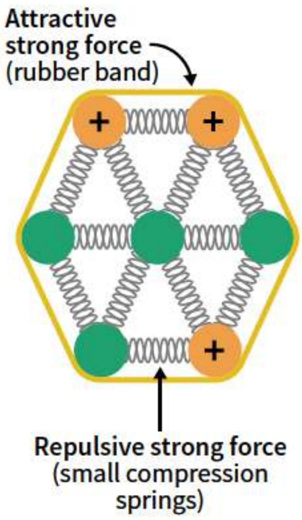


Figure 1 The strong force binds all the nucleons together, like a rubber band. It also acts like small compression springs to ensure nucleons do not get too close to each other.

Weak force

The weak force is the fundamental force responsible for certain kinds of radioactive decay.

- It interacts with fermions: in an atom, this refers to the protons, neutrons, and electrons.
- It should not be thought of as a 'push' or 'pull'.
- The weak force operates over very short distances.

The weak force is able to transform a neutron into a proton, or a proton into a neutron, by changing the flavour of a quark. This means that it changes an up quark to a down quark or vice versa. This process, which is called beta decay, will be explored further in Lesson 6D.

Electromagnetic force

The electromagnetic force is the unification of the electrostatic force (discussed in Lesson 4A) and the magnetic force. In the nucleus, the electrostatic component of the force is relevant.

- The electrostatic force acts on positively or negatively charged particles.
- The electrostatic force causes opposite charges to attract and like charges to repel.
- The strength of the force decreases as the distance between two charged particles increases.
- As shown in Figure 2, the repulsive effect of the electrostatic force in the nucleus can be thought of like strong compression springs between protons, pushing them apart.

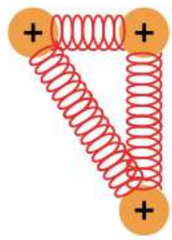


Figure 2 The electrostatic force is repulsive between protons. This can be imagined like longer compression springs between protons pushing the protons apart.

Nuclear stability 1.3.6.1

OVERVIEW

A nucleus will be stable when it has a balance between the strong force that holds nucleons together and the electrostatic force that repels protons.

THEORY DETAILS

Nuclear notation

Atoms can be represented through nuclear notation. In this notation, the identity of an element is indicated by its chemical symbol as shown on the periodic table of elements. For example, Au is the chemical symbol for gold.

- *Z* represents the number of protons in the nucleus. In all uncharged atoms, the number of protons is also the number of electrons.
- *A* represents the total number of protons and neutrons in the nucleus.
- *N* represents the number of neutrons in the nucleus. *N* is not shown in the standard nuclear notation, but can be calculated as $N = A - Z$.

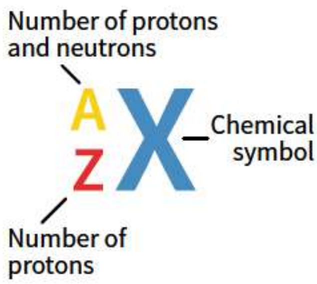


Figure 3 Nuclear notation provides information about the nucleus of a chemical element.

For example, a particular gold atom could described as:

$^{197}_{79}\text{Au}$	$Z = 79$ (79 protons in the nucleus, 79 electrons in the atom) $A = 197$ (197 total nucleons in the nucleus) $N = 197 - 79 = 118$ (118 neutrons in the nucleus)

The identity of an element is determined by Z (the number of protons in the nucleus). An atom that has the same number of protons as another atom but a different number of neutrons is called an **isotope** of that element. For example, $^{12}_{6}\text{C}$ and $^{13}_{6}\text{C}$ are both isotopes of carbon.

Nuclear stability

The nucleus is held together by binding energy. Binding energy is a quantity that depends on several factors, such as the electrostatic force pushing protons apart from each other and the strong nuclear force that is attractive between protons and neutrons.

There can be several stable isotopes for a given chemical element. In general, the strong force contribution needs to be greater than the electrostatic force pushing the positively charged protons for the nucleus to be stable.

- For atoms with an atomic number less than or equal to that of calcium ($Z = 20$), the nucleus is stable if approximately $N = Z$.

Past this point, an excess of neutrons ($N > Z$) is needed to stabilise the nucleus. This is because the electrostatic force only acts on protons in the nucleus and acts over a long range.

- Overall, every additional proton will have a large repulsive effect on the other protons due to the electrostatic force (which acts over a large range), but an almost negligible attractive effect on the protons on the other side of the nucleus due to the strong force (since it acts over such a small range). This makes the nucleus more unstable.
- In contrast, every additional neutron in the nucleus increases the attractive strong force within the nucleus without adding to the electrostatic repulsion between protons, making the nucleus more stable (to a certain extent).

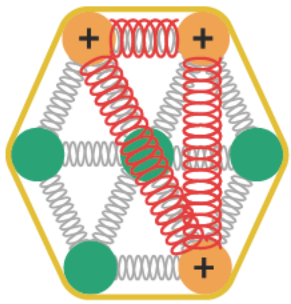


Figure 4 The stability of the nucleus depends on the relative strength of the strong force (rubber band) holding the nucleons together compared with the strength of the electrostatic force (longer red springs) repelling the protons.

There are several ways that a nucleus can be unstable.

- Too many protons per neutron
  - The electrostatic force within the nucleus repelling the protons is stronger than the strong nuclear force binding the nucleons together.
- Too big
  - When $Z \geq 84$, the nucleus contains so many repulsive protons that it becomes inherently unstable. These unstable elements, from Polonium onwards in the periodic table, are radioisotopes.
- Too many neutrons per proton
  - One of the factors contributing to binding energy is the symmetry of the nucleus. When there are more neutrons in a nucleus, the neutrons need to exist in higher energy states (due to the Pauli Exclusion Principle) which makes the nucleus more unstable.

The stability of elements can be seen on a graph of proton number (Z) versus neutron number (N) as shown in Figure 5. A line indicating $N = Z$ is commonly drawn on this graph.

- Notice that the 'Valley of Stability' follows the $N = Z$ line for the first twenty elements before diverging to favour isotopes with more neutrons than protons.
- If an isotope of an element lies above or below the Valley of Stability, it will undergo radioactive decay to become more stable. An isotope that undergoes radioactive decay is called a radioisotope.

In the process of radioactive decay, the atom will emit energy and will often emit particles. This is explored further in Lesson 6D.

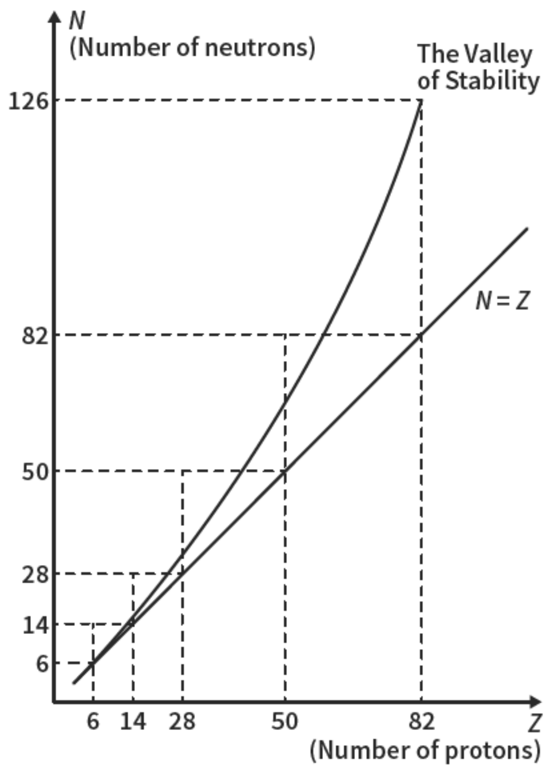


Figure 5 The Valley of Stability diagram. The curved line (referred to as the 'Valley of Stability') indicates the stable isotopes of elements. The intersections of dashed lines represent real isotopes.

Theory summary

- There are four fundamental forces: the gravitational force, the electromagnetic force, the strong force, and the weak force.
  - The strong force holds together quarks within nucleons and holds together the nucleons within the nucleus.
  - The weak force acts on quarks and is responsible for a form of radioactive decay in which a proton transforms into a neutron or vice versa to make the atom more stable.
  - The electromagnetic force acts on charged particles. It causes protons in the nucleus to be repelled.
  - The gravitational force is the weakest force and acts on particles with mass.
- Isotopes of elements can be represented in nuclear notation, where:
  - A = the number of nucleons
  - Z = the number of protons
  - N = the number of neutrons
- The primary reason a nucleus can be unstable is if there is an imbalance of forces within the nucleus.
- There are three main ways a nucleus can be unstable:
  - Having too many protons
  - Being too large ($Z \geq 84$)
  - Having too many neutrons

KEEN TO INVESTIGATE?

Hyperphysics: The Pauli Exclusion Principle
hyperphysics.phy-astr.gsu.edu/hbase/pauli.html

PhET 'Build an Atom' simulation
phet.colorado.edu/en/simulation/build-an-atom

YouTube video: Fermilab – Why is the Weak Force weak?
youtu.be/yOiABZM7wTU

YouTube video: SciShow – Strong Interaction
youtu.be/Yv3EMq2Dgq8

YouTube video: SciShow – Weak Interaction
youtu.be/cnL_nwmCLpY

CONCEPT DISCUSSION QUESTION

The strong force and the weak force are not easily observable in day to day life. Discuss the theoretical consequences of each of these forces not existing.

Answers on page 506

Hints

What particles does the strong force act on?

What processes are the weak force responsible for?

The weak force is also responsible for the fusion of hydrogen into helium. Where does this reaction occur?

6B Questions

THEORY REVIEW QUESTIONS

Question 1

The strong force is __________ (attractive/repulsive) at very short distances, and __________ (attractive/repulsive) at slightly longer distances. The strong force acts on __________ (protons/neutrons/nucleons) within the nucleus as a residual effect of holding together __________ (electrons/quarks/protons).

Question 2

Match the symbols to the provided definitions.

$$^{A}_{Z}X$$

Symbols

- A
- Z
- X

Symbol definitions

a Chemical symbol

b Number of protons in nucleus

c Number of nucleons in the nucleus

Question 3

Copy the table and, for each force, tick the properties it exhibits.

	Acts on protons	Acts on neutrons	Acts at long distances	Acts at short distances
Strong force				
Weak force				
Electromagnetic force				

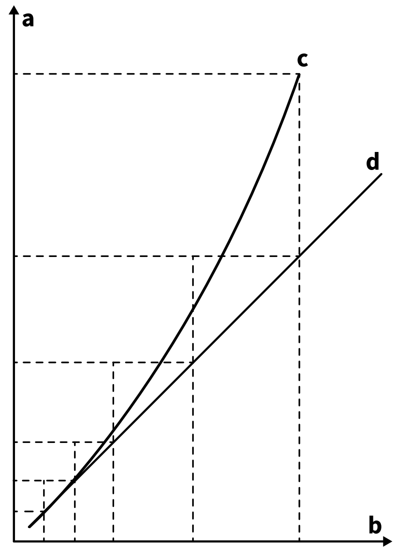
Question 4

Match each label in the diagram with an option from the word bank.

Word bank

- Valley of Stability
- *N* = *Z* line
- *Z*
- *N*

Diagram



Question 5

Carbon-14, $^{14}_{6}C$, is a radioisotope of carbon used in 'carbon dating'. Which of the following is contained in a nucleus of carbon-14?

A 6 protons only

B 6 neutrons only

C 6 electrons only

D 6 protons and 8 neutrons

E 8 protons and 6 neutrons

F 6 protons and 14 neutrons

G 8 protons and 14 electrons

Question 6

Which of the following two elements are isotopes of the same element?

A $^{84}_{37}X$

B $^{37}_{17}X$

C $^{84}_{36}X$

D $^{71}_{37}X$

DECONSTRUCTED EXAM-STYLE QUESTION

Question 7

Neon is a colourless gas that can glow when placed in an electric field, as seen when it is used in neon signs. $^{22}_{10}Ne$ is a stable isotope of neon, while $^{18}_{10}Ne$ is an unstable isotope.

Prompts

a How many protons, neutrons, and electrons are in a neutrally charged atom of $^{20}_{10}Ne$?

	Protons	Neutrons	Electrons
A	10	10	10
B	10	20	10
C	20	10	10
D	20	30	20

b The primary stability rule for elements with $Z \leq 20$ is

A there need to be more protons than neutrons.

B there need to be more neutrons than protons.

C they approximately follow $N = Z$.

D they are all inherently unstable.

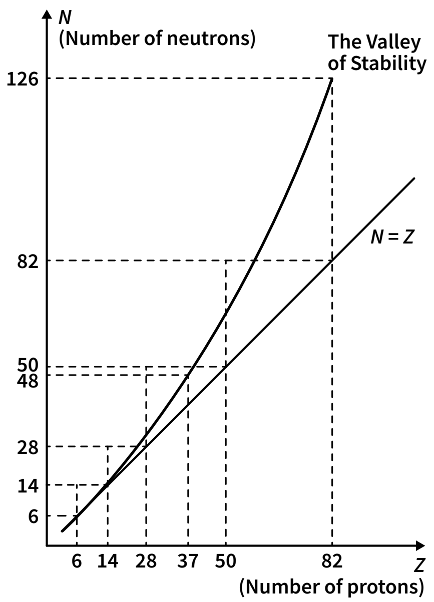
Question

c Identify whether an atom of $^{20}_{10}Ne$ is stable or unstable and explain why. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Use the following information to answer Questions 8, 9 and 15.



Question 8 (8 MARKS)

For each of the following atoms, identify if they would be stable or unstable. Briefly justify your answer with a comment or working.

a $^{32}_{16}S$ (2 MARKS)

b $^{208}_{84}Pb$ (2 MARKS)

c $^{208}_{82}Pb$ (2 MARKS)

d $^{70}_{35}Br$ (2 MARKS)

Question 9 (8 MARKS)

Determine if these unknown isotopes are going to be stable. Briefly justify your answer with a comment or working.

a $Z = 15, N = 15$ (2 MARKS)

b $N = 45, Z = 45$ (2 MARKS)

c $Z = 87, A = 223$ (2 MARKS)

d $A = 85, N = 48$ (2 MARKS)

Question 10 (2 MARKS)

Define the term isotope and distinguish between an isotope and a radioisotope.

Question 11 (2 MARKS)

Explain why a nucleus with too many protons will be unstable.

Question 12 (3 MARKS)

Jana and Genevieve, both keen physics students, are discussing the history of coins in their economics class. They are told that the most common isotope of gold ($Z = 79$) is an incredibly stable metal, which meant it was a good candidate for making coins. Jana says that the nuclear stability of gold must come from the most common isotope of gold containing an equal number of protons and neutrons in the nucleus.

Genevieve counters that the number of protons and neutrons in the nucleus could not be the same if the gold isotope were stable.

Which student is correct and why?

Previous lessons

Question 13 (3 MARKS)

Describe the construction of double glazed windows and explain why their design reduces heat transfer through the window.

Question 14 (2 MARKS)

Identify two factors that impact how severely a person is impacted by an electric shock.

Key science skills

Question 15 (3 MARKS)

This lesson has a major focus on the Valley of Stability diagram.

a Z is on the horizontal axis of the graph. Identify the kind of variable (control, independant, dependant) normally on the horizontal axis. (1 MARK)

b N is on the vertical axis of the graph. Identify the kind of variable (control, independant, dependant) normally on the vertical axis. (1 MARK)

c Explain why it is most beneficial for the usability of the Valley of Stability diagram to have Z on the horizontal axis. (1 MARK)

6C RADIOACTIVE HALF-LIFE

In Lesson 6B we learned that radioactive substances consist of unstable nuclei which decay. Different samples of radioactive substances decay at different rates. How can we measure the rates that different substances and different amounts of those substances decay? This lesson will introduce the concept of half-life as a way of measuring the decay rate of different radioisotopes and the concept of activity as a way of measuring the decay rate of a particular sample at an instant in time.

6A The Standard Model	6B Nuclear stability and the fundamental forces	6C Radioactive half-life	6D Types of nuclear radiation

Study design dot points

- describe the radioactive decay of unstable nuclei with reference to half-life
- model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives

Key knowledge units

Decay half-life	1.3.7.1
Describing decay half-lives mathematically	1.3.8.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$N = N_0\left(\frac{1}{2}\right)^n$ radioactive nuclei remaining
	$A = A_0\left(\frac{1}{2}\right)^n$ activity

Definitions for this lesson

activity (radiation) the rate of radioactive decays per unit of time

half-life the time it takes for half of a radioactive sample to decay

Decay half-life 1.3.7.1

OVERVIEW

A half-life is the time it takes for half of a substance to decay. It is used to describe the radioactive decay of unstable nuclei because such decay is a random process with a rate that is proportional to the number of nuclei remaining.

THEORY DETAILS

Suppose we flip 1000 fair coins. The result of any individual coin flip is considered random with a 50% chance of being 'heads' and a 50% chance of being 'tails'. This means that after a single trial – in which every coin is flipped – we can be confident that approximately 500 coins would land with 'heads' facing up. The number of 'heads' depends on the number of coins that we start with: if we start with 600 coins (instead of 1000 coins) we expect that approximately 300 coins would land with 'heads' facing up.

In Lesson 6B we learned that some nuclei are unstable and will eventually decay into more stable products. The radioactive decay of unstable nuclei is similar to the coin-flip process because:

- The decay of any individual nucleus is a random process – it is unpredictable.
- The approximate number of nuclei that decay in a given period of time is predictable and proportional to the initial number of nuclei.

The half-life, $t_{1/2}$, is the time it takes for a substance to decay or decrease to half (50%) of its original amount. Half-life is a useful concept for describing random decay processes where the rate of decay is proportional to the amount of the substance remaining (which is known as exponential decay).

- A shorter half-life indicates a faster rate of decay and a more unstable radioisotope.
- A longer half-life indicates a slower rate of decay and a less unstable radioisotope.

Each radioactive substance has a half-life. See Table 1 for examples.

Table 1 Some radioisotopes and their half-lives

Radioisotope	Half-life
Carbon-14	5730 years
Cesium-137	30 years
Iodine-131	8.0 days
Krypton-81m	13 seconds
Krypton-85	10.72 years
Plutonium-239	24 065 years
Polonium-214	0.00016 seconds
Rubidium-81	4.58 hours
Sodium-24	15 hours
Uranium-235	704 million years
Uranium-238	4.5 billion years

Half-life is not the same as half the time it takes for all of a substance to decay (which is impossible to predict). After one half-life, 50% of the initial substance remains and then, after a second half-life, 50% of that amount remains. That is, after two half-lives, 25% of the initial substance remains. See Figure 1.

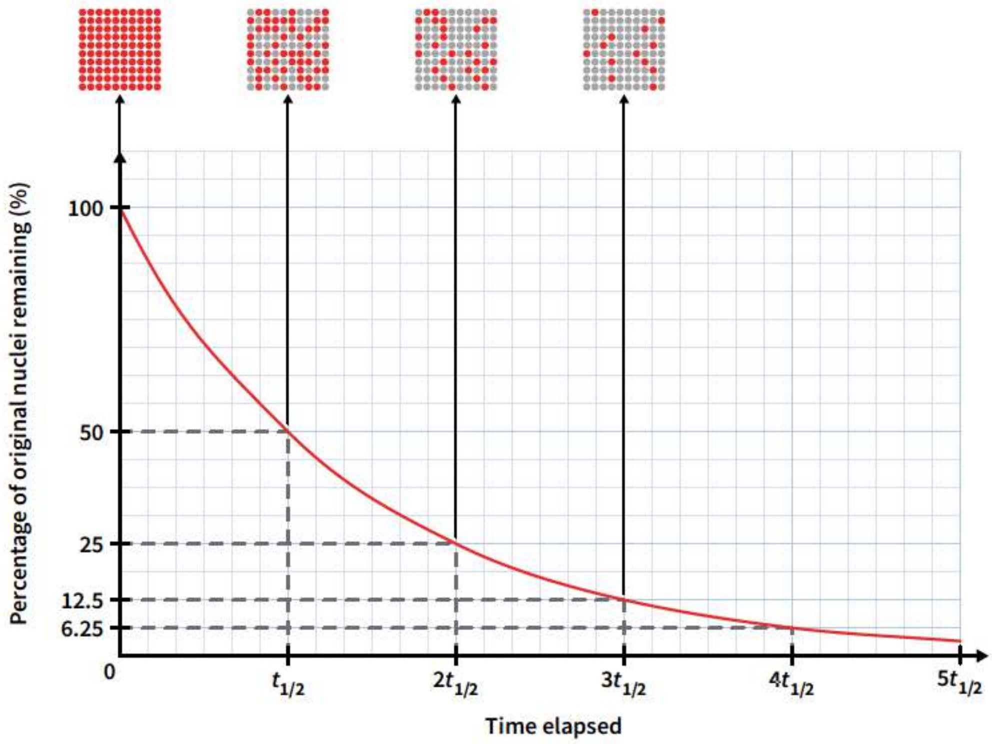


Figure 1 A graphical representation of radioactive decay

Describing decay half-lives mathematically 1.3.8.1

OVERVIEW

The amount of a radioactive substance that remains after a given number of half-lives can be calculated using an exponential decay equation.

THEORY DETAILS

If N_0 is the number of nuclei in a radioactive substance at an initial time $t = 0$:

- After one half-life, the number of nuclei remaining would be $N = N_0 \times \frac{1}{2}$.
- After two half-lives, the number of nuclei remaining would be $N = N_0 \times \frac{1}{2} \times \frac{1}{2} = N_0 \times \left(\frac{1}{2}\right)^2$.

This process leads to the following formula for calculating the number of nuclei remaining after a whole number, n, of half-lives.

$$N = N_0\left(\frac{1}{2}\right)^n$$

N = the remaining number of nuclei (no units), N_0 = the initial number of nuclei (no units), n = the number of half-lives since the initial measurement (no units)

Given that the mass of each atom is fixed for a given radioisotope, we can use a similar equation that relates the remaining mass to the initial mass: $m = m_0\left(\frac{1}{2}\right)^n$.

The number of half-lives that have elapsed in a given time period can be calculated according to the following equation:

$n = \frac{T}{t_{1/2}}$ where T is the time period and $t_{1/2}$ is the half-life of the substance.

Worked example 1

A sample of the artificial radioisotope sodium-24, which has a half-life of 15 hours, initially contains 16×10^{12} nuclei.

a How many nuclei remain after 45 hours?

b How long does it take until 5.0×10^{11} nuclei remain?

Working	Process of thinking
a $n = \frac{T}{t_{1/2}} = \frac{45}{15} = 3$ half-lives	Calculate how many half-lives elapsed in 45 hours.
$N = N_0\left(\frac{1}{2}\right)^n$ $N = 16 \times 10^{12} \times \left(\frac{1}{2}\right)^3$ $N = 2.0 \times 10^{12}$ nuclei	Substitute $N_0 = 16 \times 10^{12}$ and $n = 3$ into the equation relating the initial number of nuclei to the number of nuclei remaining.
b $N = N_0\left(\frac{1}{2}\right)^n$ $5.0 \times 10^{11} = 16 \times 10^{12} \times \left(\frac{1}{2}\right)^n$	Substitute $N_0 = 16 \times 10^{12}$ and $N = 5.0 \times 10^{11}$ into the equation relating the initial number of nuclei to the number of nuclei remaining.
$\left(\frac{1}{2}\right)^n = \frac{5.0 \times 10^{11}}{16 \times 10^{12}} = 0.03125$	Transpose the equation to make $\left(\frac{1}{2}\right)^n$ the subject.
$0.03125 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^5$ $\therefore n = 5$ half-lives	Repeatedly multiply $\frac{1}{2}$ with itself until we reach 0.03125 to determine the number of half-lives. Alternatively use $n = \frac{\log(0.03125)}{\log(1/2)} = 5$. Logarithms are beyond the scope of VCE Physics but they can be used.
So it takes 5 × 15 hours = 75 hours.	Convert the number of half-lives to the number of hours.

It is common to quantify the rate of radioactive decay at an instant in time by its 'activity', which measures the number of nuclei decaying per unit of time. The SI unit for activity is the becquerel (Bq), where 1 Bq = 1 nucleus decay per second. The rate of decay of a radioactive substance is proportional to the amount of the substance remaining, which means we can use a very similar formula to relate activity at any point in time to the initial activity.

$$A = A_0\left(\frac{1}{2}\right)^n$$

A = the activity at a given time (Bq), A_0 = the initial activity (Bq), n = the number of half-lives since the initial measurement (no units)

Worked example 2

A sample of the artificial radioisotope technetium-99m, which has a half-life of 6 hours, has an initial activity of 8000 Bq. Determine the activity of the sample after one full day.

Working	Process of thinking
$n = \frac{T}{t_{1/2}} = \frac{24}{6} = 4$ half-lives	Calculate how many half-lives elapsed in 24 hours.
$A = A_0\left(\frac{1}{2}\right)^n$ $A = 8000 \times \left(\frac{1}{2}\right)^3$ $A = 500$ Bq	Substitute $A_0 = 8000$ and $n = 4$ into the equation relating the initial activity to the activity after n half-lives.

Theory summary

- The decay of an individual unstable nucleus is a random process, which means we cannot predict when it will occur.
- A half-life is a measurement of time. It is the time it takes for half of a radioactive sample to decay and it indicates how unstable a radioisotope is.
- The value of the half-life is fixed for each radioisotope.
- Activity measures the decay rate of a radioactive substance at an instant in time. It is measured in becquerels (Bq) where 1 Bq = 1 nucleus decay per second.
- After n half-lives have passed since an initial measurement:
  - The number of nuclei remaining is given by $N = N_0\left(\frac{1}{2}\right)^n$
  - The activity is given by $A = A_0\left(\frac{1}{2}\right)^n$

KEEN TO INVESTIGATE?

Duffy, Andrew. 'Half-life' simulation
physics.bu.edu/~duffy/HTML5/halflife.html

YouTube video: Cognito – GCSE Physics – Radioactive Decay and Half Life
youtu.be/zXw2cOSBB8E

YouTube video: Scientific American – How Does Radiocarbon Dating Work?
youtu.be/phZeE7Att_s

CONCEPT DISCUSSION QUESTION

Consider a bottle that contains one litre of water that is being emptied at a constant rate of 100 mL per second.

Discuss why the concept of a half-life (i.e. the time it takes for the volume of water to decrease by 50%) does not apply to this situation.

Answers on page 506

Hints

How long does it take for the volume of water in the bottle to decrease to half of its original volume?

How much additional time does it take for the volume of water to decrease to half of that volume?

How does this rate of decrease compare to the decay of radioactive substances?

6C Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1 and 2.

The half-life of substance *X* is one hour. Initially, there is 10 grams of substance *X* in a sample.

Question 1

How long does it take for all 10 grams of the substance to decay?

A One hour

B Two hours

C More than two hours

Question 2

How much of substance *X* remains after two hours?

A None

B 2.5 grams

Question 3

Half-life is a way to measure the decay rate of a substance. Which of the following statements is/are true when describing the half-life for a given sample of a radioisotope? *(Select all that apply)*

A The half-life depends on what the radioisotope is.

B The half-life depends on how much of the substance there is.

C The half-life changes as time passes.

Question 4

Activity is a way to measure the decay rate of a substance. Which of the following statements is/are true when describing the activity for a given sample of a radioisotope? *(Select all that apply)*

A The activity depends on what the radioisotope is.

B The activity depends on how much of the substance there is.

C The activity changes as time passes.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 5 (4 MARKS)

A medical tracer that contains 24 milligrams of phosphorus-32 is stored at a hospital. In 28 days, only six milligrams of the original phosphorus-32 remains.

Prompts

a What is six milligrams as a proportion of the original 24 milligrams?

A 0.25

B 0.5

C 0.75

D 4

b How many half-lives must elapse so that only six milligrams of the original phosphorus-32 remains?

A 1

B 2

C 3

D 4

c Based on this data, which option is closest to the half-life of phosphorus-32?

A 7 days

B 9 days

C 14 days

D 28 days

Question

d How long will it take in total until only 1.5 milligrams of the original phosphorus-32 remains? (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 6 (3 MARKS)

A radioactive sample has an initial mass of 0.840 grams.

a What mass of the radioactive sample remains after three half-lives? (1 MARK)

b What mass of the radioactive sample has decayed after four half-lives? (2 MARKS)

Question 7 (4 MARKS)

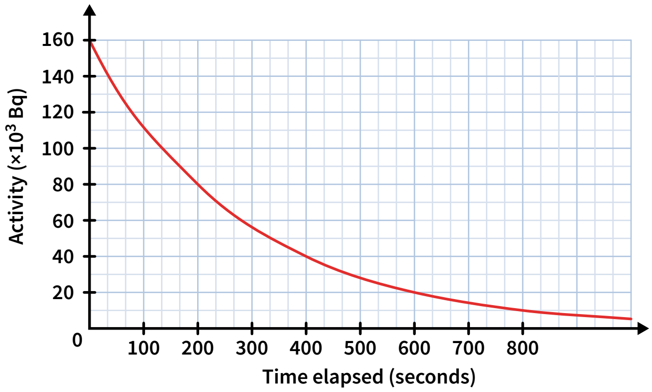
Iodine-131 has a half-life of 8.0 days. A sample of iodine-131 initially contains 5.0×10^{10} atoms.

a Calculate the number of iodine-131 atoms that remain after 8 weeks. (2 MARKS)

b Calculate how long it takes until only 6.25×10^{9} iodine-131 atoms remain. (2 MARKS)

Question 8 (5 MARKS)

The graph shows the activity of an unknown radioisotope.



a Use the graph to determine the half-life of the unknown radioisotope. (1 MARK)

b Calculate the activity of the sample after 20 minutes. (2 MARKS)

c If there was 40 grams of this sample to begin with, calculate how much of the sample remains after 400 seconds. (2 MARKS)

Question 9 (3 MARKS)

A sample of sodium-24, which has a half-life of 15 hours, has been left in a laboratory for 90 hours. At the present time, the activity of the sample is 5000 Bq. Calculate the activity of the sample when it was first put in the laboratory.

Question 10 (4 MARKS)

A 50 milligram sample of cobalt-60 decays so that only 12.5 milligrams remains after 10.6 years. How long will it take in total until only 6.25 milligrams of the original cobalt-60 remains?

Previous lessons

Question 11 (4 MARKS)

Explain how the use of eaves above windows can assist with energy-efficient house designs. Use a diagram to assist your explanation.

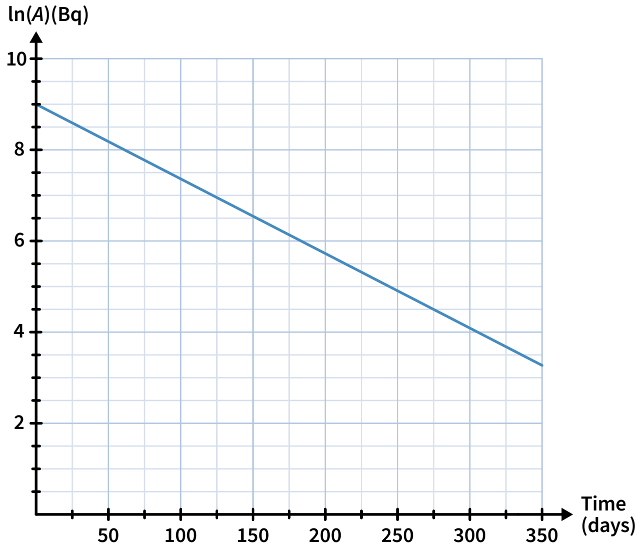
Question 12 (2 MARKS)

Compare the purposes of an electrical fuse with a residual current device (RCD).

Key science skills

Question 13 (4 MARKS)

Scientists use a Geiger counter to measure the activity of an unknown radioactive isotope over one year. They plot the natural logarithm of the activity (ln(*A*)) against time as shown.



a Calculate the gradient of the graph. (2 MARKS)

b It is known that the equation of the graph takes the form $\ln(A) = -\frac{0.693}{t_{1/2}} \times t + 9$. Given that the equation of a straight line can be expressed in the form $y = mx + c$ where m is the gradient of the line, use the gradient calculated in part **a** to determine the half-life, $t_{1/2}$, of the substance to the nearest day. (2 MARKS)

6D TYPES OF NUCLEAR RADIATION

In Lesson 6B we investigated radioisotopes, which are unstable isotopes that can become more stable through processes of radioactive decay. This lesson introduces the four main forms of radioactive decay (alpha radiation, beta minus radiation, beta plus radiation, and gamma radiation) as well as nuclear decay equations.

6A The Standard Model	6B Nuclear stability and the fundamental forces	6C Radioactive half-life	6D Types of nuclear radiation

Study design dot points

- apply a simple particle model of the atomic nucleus to explain the origin of α, β^-, β^+ and γ radiation, including changes to the number of nucleons
- explain nuclear transformations using decay equations involving α, β^-, β^+ and γ radiation
- analyse decay series diagrams with reference to type of decay and stability of isotopes

Key knowledge units

Alpha radiation	1.3.9.1 & 1.3.10.1
Beta minus radiation	1.3.9.2 & 1.3.10.2
Beta plus radiation	1.3.9.3 & 1.3.10.3
Gamma radiation	1.3.9.4 & 1.3.10.4
Decay series diagrams	1.3.11.1

No previous or new formulas for this lesson

Definitions for this lesson

alpha decay the process by which an unstable nucleus decays into a more stable nucleus by emitting an alpha particle

alpha particle a particle composed of two protons and two neutrons (the nucleus of a standard helium atom)

beta minus decay the process by which an unstable nucleus decays into a more stable nucleus by transforming a neutron into a proton and emitting an electron and an antineutrino

beta particle an electron (beta minus decay) or a positron (beta plus decay)

beta plus decay the process by which an unstable nucleus decays into a more stable nucleus by transforming a proton into a neutron and emitting a positron and a neutrino

gamma decay the process by which an excited nucleus decays into a more stable nucleus by emitting energy in the form of gamma rays

gamma rays high energy photons

ionisation energy the energy required to remove an electron from an atom

ionising power the ability of a given type of radiation to cause another atom to lose electrons and become an ion

nuclide a nucleus with a specific number of neutrons and protons

penetrating power an indicator of the extent to which a given type of radiation can penetrate matter before it loses its energy

radiation any type of energy, or energy-carrying particles, that spreads as it travels away from a source

Alpha radiation 1.3.9.1 & 1.3.10.1

OVERVIEW

Nuclear decay can be analysed through nuclear decay equations. In alpha decay, an unstable nucleus decays by emitting an alpha particle.

THEORY DETAILS

Nuclear decay equations

Nuclear decay equations represent nuclear decay processes. A nuclide called the parent nuclide on the left-hand side of the equation decays into the daughter nuclide and other products such as energy on the right-hand side.

Parent nuclide ⟶ Daughter nuclide + other products

Figure 1 The general form of a nuclear decay equation

As we introduced in 6B, in nuclear equation notation, the symbol for a nuclide is written with a superscript that indicates the mass number of the nuclide and a subscript that indicates the atomic number of the nuclide. Noting that the atomic number is the charge of the nucleus, this notation can be extended to other particles by having the superscript be the mass in atomic units and the subscript be the charge.

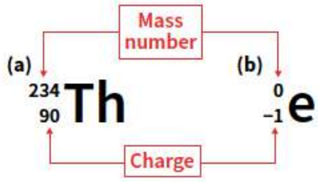


Figure 2 The nuclear notation for **(a)** the thorium-234 nuclide and **(b)** an electron. The electron is assigned a mass number of 0 because its mass is negligible when compared to that of a proton or neutron.

Nuclides can also be represented by their chemical name followed by their mass number. For example, the isotope of thorium shown in Figure 2 is called thorium-234.

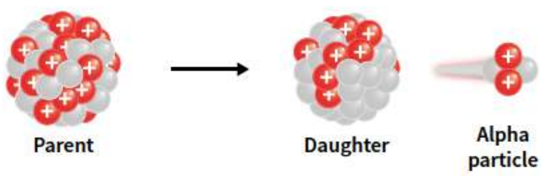
In a nuclear decay process, the mass number and the total charge are conserved. This means that both the sum of all the subscripts and the sum of all the superscripts on both sides of the equation need to be equal. For example, on both sides of the carbon-14 decay equation below the sum of the superscripts is equal to 14, and the sum of the subscripts is equal to 6.

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\bar{\nu}$$

Alpha radiation

An alpha particle is composed of two protons and two neutrons (therefore having a +2 charge) and is the most prevalent isotope of helium. It is represented by any one of the following symbols: $^{4}_{2}\alpha$, $^{4}_{2}\text{He}$, or α.

- Alpha decay occurs in heavy, unstable elements that have too many protons compared to their number of neutrons.
- The parent nuclide decays into the daughter nuclei by emitting an alpha particle.
  - The atomic number of the daughter nuclide is 2 less than the atomic number of the parent nuclide.
  - The mass number of the daughter nuclide is 4 less than the mass number of the parent nuclide.
- Energy is also released in this decay in the form of the kinetic energy given to the ejected particles and daughter nuclide.



$$^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\text{He}$$

Figure 3 In alpha decay, the parent nuclide emits an alpha particle.

An example of an alpha decay process is:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

Ionising power refers to the ability of a given type of radiation to cause other atoms to lose electrons and become ions. Ionising radiation is dangerous because when atoms in cells are ionised, they can mutate which can then cause cancer.

Alpha particles are highly ionising due to their +2 charge, which causes electrons in other atoms to be strongly attracted to the alpha particle. In effect, the alpha particle is able to pull electrons off the atoms it passes by. When the alpha particle has dissipated its kinetic energy through ionising other atoms, it becomes a neutral helium atom by gaining two electrons.

Penetrating power is an indicator of the extent to which a given type of radiation can penetrate matter before it loses its energy. Relative to other forms of radiation, alpha particles have a low penetrating power due to their larger mass, which results in alpha particles having lower average speeds and more interactions with other atoms. The strong ionising power of alpha radiation is therefore directly related to its weaker penetrating power. Alpha particles can only travel a few centimetres in air before being absorbed (becoming stable helium).

Beta minus radiation 1.3.9.2 & 1.3.10.2

OVERVIEW

In beta minus decay, a neutron in the nucleus decays into a proton, an electron, and an antineutrino.

THEORY DETAILS

A beta minus particle is an electron. It is represented by any one of the following symbols: ${}^{0}_{-1}\beta$, ${}^{0}_{-1}e$, or β^-.

- Beta minus decay occurs in nuclides that have too many neutrons relative to the number of protons.
- The process involves a neutron in the parent nuclide decaying into a proton in the daughter nuclide and the ejection of an electron and an antineutrino.
  - The atomic number of the daughter nuclide is one more than the atomic number of the parent nuclide.
  - The mass number of the daughter nuclide is the same as the mass number of the parent nuclide.
- Energy is released in this decay in the form of the kinetic energy of the daughter nuclide, electron, and antineutrino.

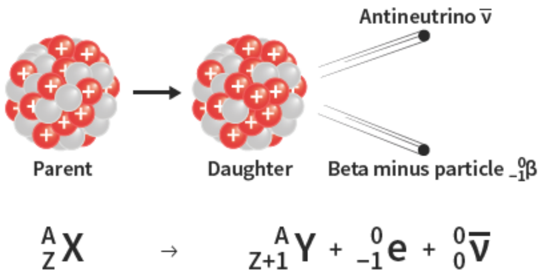


Figure 4 In beta minus decay, a neutron in the parent nuclide turns into a proton and the parent nuclide emits an electron and antineutrino.

The decay of a neutron into a proton in beta minus decay:

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{v}$$

An example of a beta minus decay process is:

$${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e + {}^{0}_{0}\bar{v}$$

- Beta minus particles have higher penetrating ability than alpha particles because they are much lighter and so can travel faster.
  - While an alpha particle would be stopped by a piece of paper, a beta minus particle would be stopped by a thin aluminium plate.
- Beta minus particles are less ionising than alpha particles due to only having a single negative charge. They are able to ionise other atoms by transferring some of their kinetic energy to the atoms they collide with (transferring at least the ionisation energy of the atom) until the beta minus particle is absorbed.

Beta plus radiation 1.3.9.3 & 1.3.10.3

OVERVIEW

In beta plus decay, a proton in the nucleus decays into a neutron, a positron and a neutrino.

THEORY DETAILS

A beta plus particle is a positron. It is represented by any one of the following symbols: ${}^{0}_{+1}\beta$, ${}^{0}_{+1}e$, or β^+.

- Beta plus decay occurs in nuclides that have too many protons relative to the number of neutrons.
- The process involves a proton in the parent nuclide decaying into a neutron in the daughter nuclide and the ejection of a positron and a neutrino.
  - The atomic number of the daughter nuclide is one less than the atomic number of the parent nuclide.
  - The mass number of the daughter nuclide is the same as the mass number of the parent nuclide.
- Energy is released in this decay in the form of the kinetic energy of the daughter nuclide, positron, and neutrino.

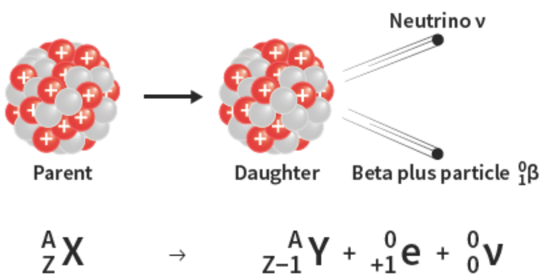


Figure 5 In beta plus decay, a proton in the parent nuclide turns into a neutron and the parent nuclide emits a positron and neutrino.

The decay of a proton into a neutron in beta plus decay:

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}v$$

An example of a beta plus decay process is:

$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + ^{0}_{+1}e + ^{0}_{0}v$

- Beta plus particles have the same penetration and ionisation power as beta minus particles.
  - They have higher penetrating ability than alpha particles, because they are much lighter and so can travel faster. They can be stopped by a thin aluminium plate.
  - They are less ionising than alpha particles due to only having a single negative charge.

Gamma radiation 1.3.9.4 & 1.3.10.4

OVERVIEW

In gamma decay, an excited nucleus decays into a stable nucleus by emitting energy in the form of gamma rays.

THEORY DETAILS

A gamma ray is a high energy photon. It is represented by the symbol $^{0}_{0}\gamma$ or γ.

Following a decay process, a nuclide can be left in an excited state (it has 'extra' energy). This energy is radiated from the nuclide as gamma rays to make the nuclide stable in its ground state.

- Gamma decay occurs in nuclides that are excited.
- The atomic number and mass number of the daughter nuclide are the same as those of the parent nuclide.
- Energy is released in this decay in the form of the gamma rays.
- Gamma radiation is often emitted alongside another form of radiation (alpha or beta).

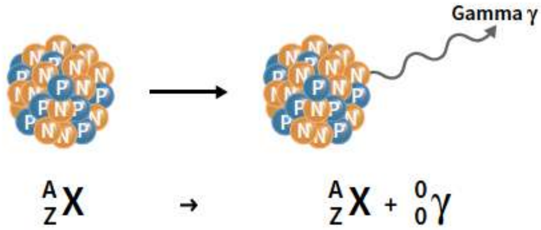


Figure 6 In gamma decay, an excited nuclide emits energy in the form of gamma rays (high-energy photons).

An example of a gamma decay process is:

$^{60}_{28}Ni \rightarrow ^{60}_{28}Ni + ^{0}_{0}\gamma$

- Gamma radiation has the greatest penetrating ability because photons are massless, travel at the speed of light, and have no electric charge. Gamma rays require many centimetres of a dense material like lead to be absorbed.
- Due to gamma rays having no electric charge, gamma radiation is less ionising than alpha radiation and beta radiation. It can ionise by imparting the ionisation energy to an electron in an atom or by a photon colliding directly with an electron which causes the electron to recoil.

Decay series diagrams 1.3.11.1

OVERVIEW

A decay series diagram plots the nuclides formed in the successive decays of an unstable parent nuclide until the daughter nuclide is stable.

THEORY DETAILS

The daughter nuclide in a radioactive decay process is not always stable. When the daughter nuclide is unstable, it will undergo further radioactive decay until a stable nuclide is produced.

The process of repeated radioactive decay is called a decay series, and can be represented as a decay series diagram. We will primarily consider decay series diagrams that plot mass number against the number of protons, like in Figure 8, which shows the decay series of uranium-238. However, plotting the number of neutrons against the number of protons is also common.

In a decay series diagram of the mass number against the number of protons:

- Alpha decay is represented by an arrow that points down and left because the atomic and mass number both decrease. See Figure 7(a).
- Beta minus decay is represented by a horizontal arrow to the right because the proton number increases by one while the mass number is constant. See Figure 7(b).
- Beta plus decay is represented by a horizontal arrow to the left because the proton number decreases by one while the mass number is constant. See Figure 7(c).

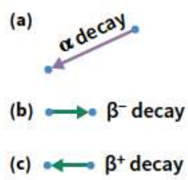


Figure 7 On a decay series diagram of mass number versus the number of protons, **(a)** alpha decay is represented by an arrow pointing down and to the left, **(b)** beta minus decay is represented by a horizontal arrow to the right, and **(c)** beta plus decay is represented by a horizontal arrow to the left.

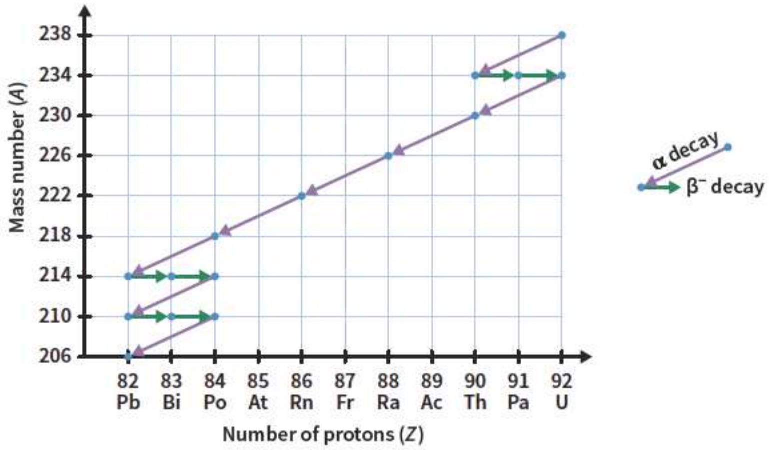


Figure 8 The decay series of uranium-238. The final daughter nuclide of the series is lead-206.

Theory summary

	When radiation occurs	Daughter nuclide proton number	Daughter nuclide mass number	Other products	Penetrating power	Ionising power
Alpha radiation	Heavy nuclides with too many protons	Z−2	A−4	$^{4}_{2}He$	Least	Greatest
Beta minus radiation	Nuclides with too many neutrons	Z+1	A	$^{0}_{-1}e + ^{0}_{0}\bar{v}$	Medium	Medium
Beta plus radiation	Nuclides with too many protons	Z−1	A	$^{0}_{+1}e + ^{0}_{0}v$	Medium	Medium
Gamma radiation	Excited nuclides	Z	A	$^{0}_{0}\gamma$	Greatest	Least

KEEN TO INVESTIGATE?

PhET 'Beta decay' simulation

phet.colorado.edu/en/simulation/beta-decay

PhET 'Alpha decay' simulation

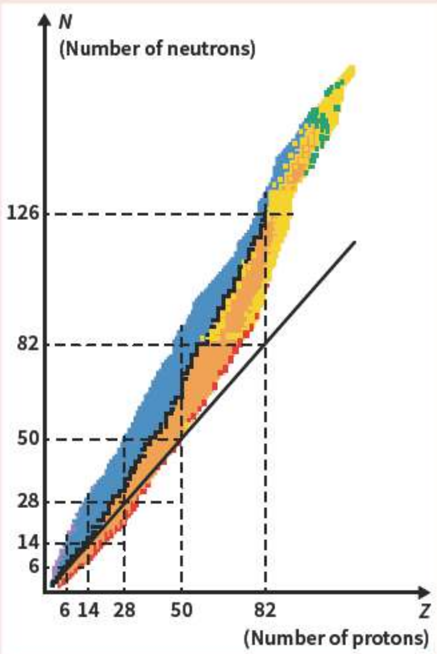
phet.colorado.edu/en/simulation/legacy/alpha-decay

CONCEPT DISCUSSION QUESTION

The Valley of Stability diagram introduced in Lesson 6B can also indicate the kind of decay that each radioactive nuclide undergoes. In the diagram shown here, each colour represents a different kind of decay.

Discuss which colour (out of blue, yellow and orange) represents which kind of decay (alpha, beta plus or beta minus) and why.

Answers on page 506



Hints

Are the nuclides on the Valley of Stability line stable or unstable?

Does beta plus decay or beta minus decay increase the number of protons in a nuclide?

What kind of nuclides undergo alpha decay?

6D Questions

THEORY REVIEW QUESTIONS

Question 1

a State the charge and mass number of the alpha particle, α.

b State the charge and mass number of the beta plus particle, β^+.

c State the charge and mass number of the beta minus particle, β^-.

d State the charge and mass number of a gamma ray (photon), γ.

Question 2

Identify which kind of decay (alpha, beta minus, beta plus, or gamma) is represented by the following equations.

a ${}^{24}_{12}Mg \rightarrow {}^{24}_{12}Mg + {}^{0}_{0}\gamma$

b ${}^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{+1}e + {}^{0}_{0}v$

c ${}^{224}_{88}Ra \rightarrow {}^{220}_{86}Rn + {}^{4}_{2}He$

d ${}^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e + {}^{0}_{0}\overline{v}$

Question 3

Select the list that correctly states the penetrating ability of alpha, beta, and gamma radiation in increasing order.

A gamma, beta, alpha

B alpha, beta, gamma

C alpha, gamma, beta

D beta, alpha, gamma

Question 4

Select the list that correctly states the ionising ability of alpha, beta and gamma radiation in increasing order.

A gamma, beta, alpha

B alpha, beta, gamma

C alpha, gamma, beta

D beta, alpha, gamma

Question 5

Identify the kind of decay that would be most likely to occur in the following nuclides:

a A heavy, unstable isotope with too many protons

b A light, unstable isotope with too many protons

c An unstable isotope with too many neutrons

d An unstable, excited isotope

DECONSTRUCTED EXAM-STYLE QUESTION

Question 6 (3 MARKS)

Prompts

Thorium-232 is the most stable isotope of thorium, having a half life of over 14 billion years. However, thorium-232 undergoes a series of radioactive decay reactions to eventually decay to a stable daughter nuclide.

a Identify the proton number, neutron number, and mass number of ${}^{232}_{90}Th$.

	Proton number	Neutron number	Mass number
A	90	232	142
B	90	142	232
C	232	90	142
D	142	90	232

b Identify how the proton number changes between the parent nuclide and daughter nuclide under the different radioactive decay processes.

	Alpha decay	Beta plus decay	Beta minus decay
A	−2	+1	−1
B	−4	−1	−1
C	−2	−1	+1
D	−4	+1	+1

c Identify how mass number changes between the parent nuclide and daughter nuclide under the different radioactive decay processes.

	Alpha decay	Beta plus decay	Beta minus decay
A	−2	+1	−1
B	−2	0	−1
C	−4	0	0
D	−4	+1	0

Question

d In its decay series, thorium-232 (${}^{232}_{90}Th$) undergoes six alpha decays and four beta minus decays. Identify the resulting daughter nuclide. (3 MARKS)

Data:

Atomic number	Element
80	Mercury (Hg)
81	Thallium (Tl)
82	Lead (Pb)
83	Bismuth (Bi)
84	Polonium (Po)

EXAM-STYLE QUESTIONS

This lesson

Question 7 (3 MARKS)

Explain why the ionising power and penetrating power of the different forms of radiation are inversely related.

Question 8 (4 MARKS)

Fill in the blanks in the following decay equations with the appropriate particles (note that there can be more than one particle).

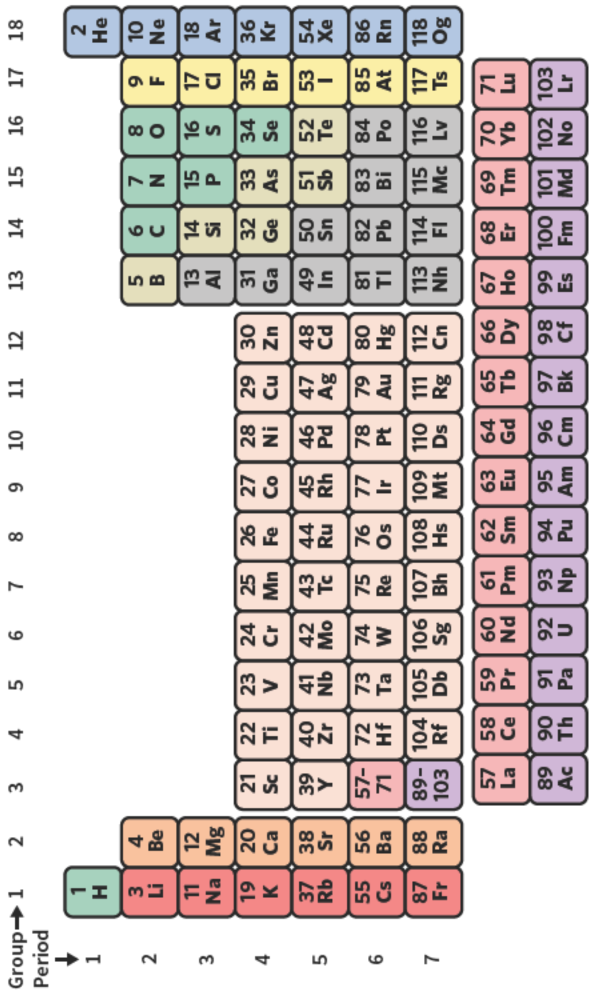
a $^{14}_{6}C \rightarrow ^{14}_{7}B + \ldots$ (1 MARK)

b $^{149}_{64}Gd \rightarrow ^{145}_{62}Sm + \ldots$ (1 MARK)

c $^{137}_{56}Ba \rightarrow ^{137}_{56}Ba + \ldots$ (1 MARK)

d $^{10}_{6}C \rightarrow ^{10}_{5}B + \ldots$ (1 MARK)

Use the following information to answer Questions 9–12.



Question 9 (8 MARKS)

Fill in the blanks in the following decay equations with the appropriate daughter nuclide.

a $^{175}_{78}Pt \rightarrow \ldots + ^{4}_{2}He$ (2 MARKS)

b $^{228}_{88}Ra \rightarrow \ldots + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$ (2 MARKS)

c $^{23}_{12}Mg \rightarrow \ldots + ^{0}_{+1}e + ^{0}_{0}\nu$ (2 MARKS)

d $^{125}_{53}I \rightarrow \ldots + ^{0}_{0}\gamma$ (2 MARKS)

Question 10 (8 MARKS)

Fill in the blanks in the following decay equations with the appropriate parent nuclide.

a $\ldots \rightarrow ^{22}_{10}Ne + ^{0}_{0}\gamma$ (2 MARKS)

b $\ldots \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$ (2 MARKS)

c $\ldots \rightarrow ^{233}_{91}Pa + ^{4}_{2}He$ (2 MARKS)

d $\ldots \rightarrow ^{74}_{35}Br + ^{0}_{+1}e + ^{0}_{0}\nu$ (2 MARKS)

Question 11 (8 MARKS)

a Write the equation for the alpha decay of $^{215}_{85}At$. (2 MARKS)

b Write the equation for the beta plus decay of $^{64}_{29}Cu$. (2 MARKS)

c Write the equation for the beta minus decay of $^{223}_{87}Fr$. (2 MARKS)

d Write the equation for the gamma decay of $^{72}_{34}Se$. (2 MARKS)

Question 12 (7 MARKS)

Neptunium-237 $\left(^{237}_{93}Np\right)$ undergoes the following radioactive decays in sequence:

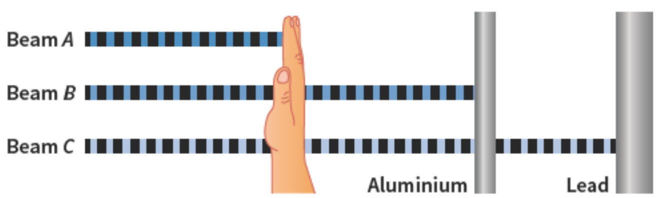
- 1 alpha decay
- 1 beta minus decay
- 2 alpha decays
- 1 beta minus decay
- 4 alpha decays
- 2 beta minus decays
- 1 alpha decay

a Identify the stable nuclide product of this decay series. (3 MARKS)

b Sketch the decay series diagram for neptunium-237. Plot the number of protons on the horizontal axis and the mass number on the vertical axis. (4 MARKS)

Question 13 (3 MARKS)

Identify the kind of radiation labelled Beam *A*, Beam *B* and Beam *C*, respectively.



Question 14 (3 MARKS)

Describe how alpha decay, beta minus decay, and beta plus decay would be represented on a decay series diagram that plotted the number of neutrons (vertical axis) against the number of protons (horizontal axis).

Previous lessons

Question 15 (4 MARKS)

A light bulb runs for 10 hours and uses 432 kJ of energy over this period.

a Calculate the power consumption of the light bulb in watts. (2 MARKS)

b If the light bulb draws 2.0 A of current, calculate the voltage supplied to the light bulb. (2 MARKS)

Question 16 (3 MARKS)

Define a positron and explain what would happen if a positron and an electron interacted.

Key science skills

Question 17 (6 MARKS)

The mass of an alpha particle is approximately 6.64466×10^{-27} kg.

a State the number of significant figures given in this mass value. (1 MARK)

The kinetic energy of an alpha particle ejected during alpha decay is 5.00 MeV. Note that 1 eV = 1.602×10^{-19} J.

b Calculate the kinetic energy of the alpha particle in joules. (2 MARKS)

c If the kinetic energy of a particle is given by $KE = \frac{1}{2} m v^2$, where m represents the particle mass and v represents the particle velocity in SI units, calculate the velocity of the alpha particle to the correct number of significant figures. (3 MARKS)

CHAPTER 6 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Which is the best description of quarks?

A Particles that are electrically neutral

B Force carrier particles

C Particles that are made up of subatomic particles

D Components of subatomic particles

Question 2

Which of the following properties is **not** exhibited by the strong force?

A It acts over large distances compared to the other fundamental forces.

B It acts between nucleons.

C It acts between quarks.

D It is always attractive.

Question 3

When an atom undergoes β^- decay

A it loses one of the electrons surrounding its nucleus.

B the mass number decreases by 1 and the atomic number stays the same.

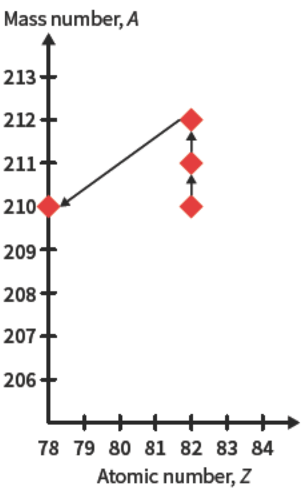
C the mass number increases by 1 and the atomic number stays the same.

D the mass number stays the same and the atomic number increases by 1.

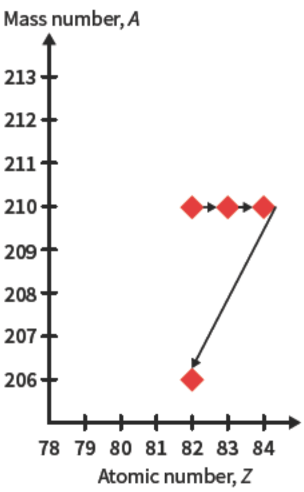
Question 4

The atomic number of lead is 82. Lead-210 is a radioactive isotope that decays by two β^- emissions followed by an α emission. Which of the following graphs best represents this decay process?

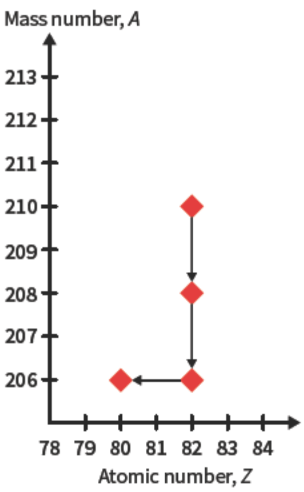
A



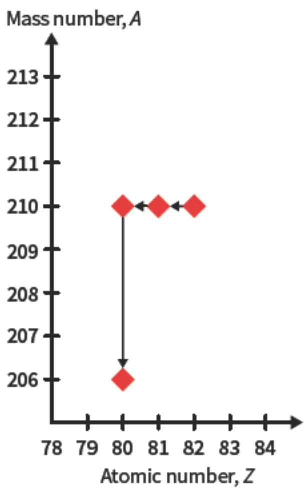
B



C



D



Question 5

A substance has a half-life of 10 years. How long does it take for the activity of the substance to decrease by 75% from its original value?

A 7.5 years

B 13.3 years

C 15 years

D 20 years

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (3 MARKS)

The tau particle (τ) has a mass of 3.17×10^{-27} kg and a charge of $-e$.

a Identify the mass and charge of the corresponding antiparticle. (2 MARKS)

b Describe what would happen if the tau particle came into contact with its antiparticle. (1 MARK)

Question 7 (3 MARKS)

Compare the composition of mesons with baryons and identify the force that binds each one together.

Question 8 (3 MARKS)

Any nucleus with 84 protons (corresponding to polonium) or more is unstable (radioactive). Explain what makes a nucleus stable and why large nuclei tend to be less stable than small nuclei.

Question 9 (2 MARKS)

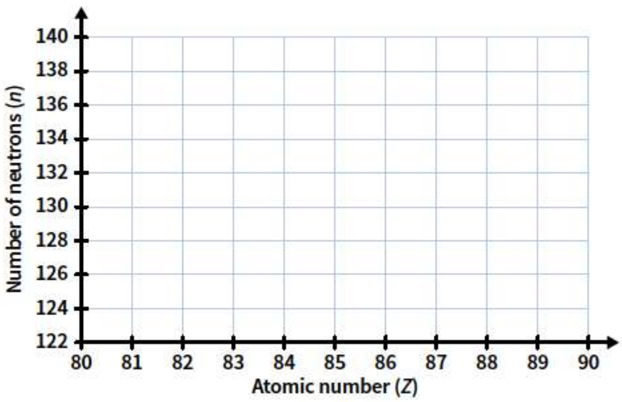
Identify which of the naturally occurring forms of radiation results in the nucleus becoming smaller. Describe the changes to the nucleus that occur when this radiation is emitted.

Question 10 (4 MARKS)

Radon has an atomic number of 86. Radon-222 is a radioactive isotope which decays by:

- two α emissions,
- followed by two β^- emissions,
- followed by one α emission,
- followed by two β^- emissions,
- followed by one α emission.

On a set of axes like the one provided, show this decay series. Note that in this case the vertical axis shows the number of neutrons (rather than the mass number).



Question 11 (4 MARKS)

In each part of this question, an incomplete decay equation is shown. Complete the equations including the missing mass numbers.

a $^{?}_{19}K \rightarrow ^{40}_{18}Ar + \ldots$ (2 MARKS)

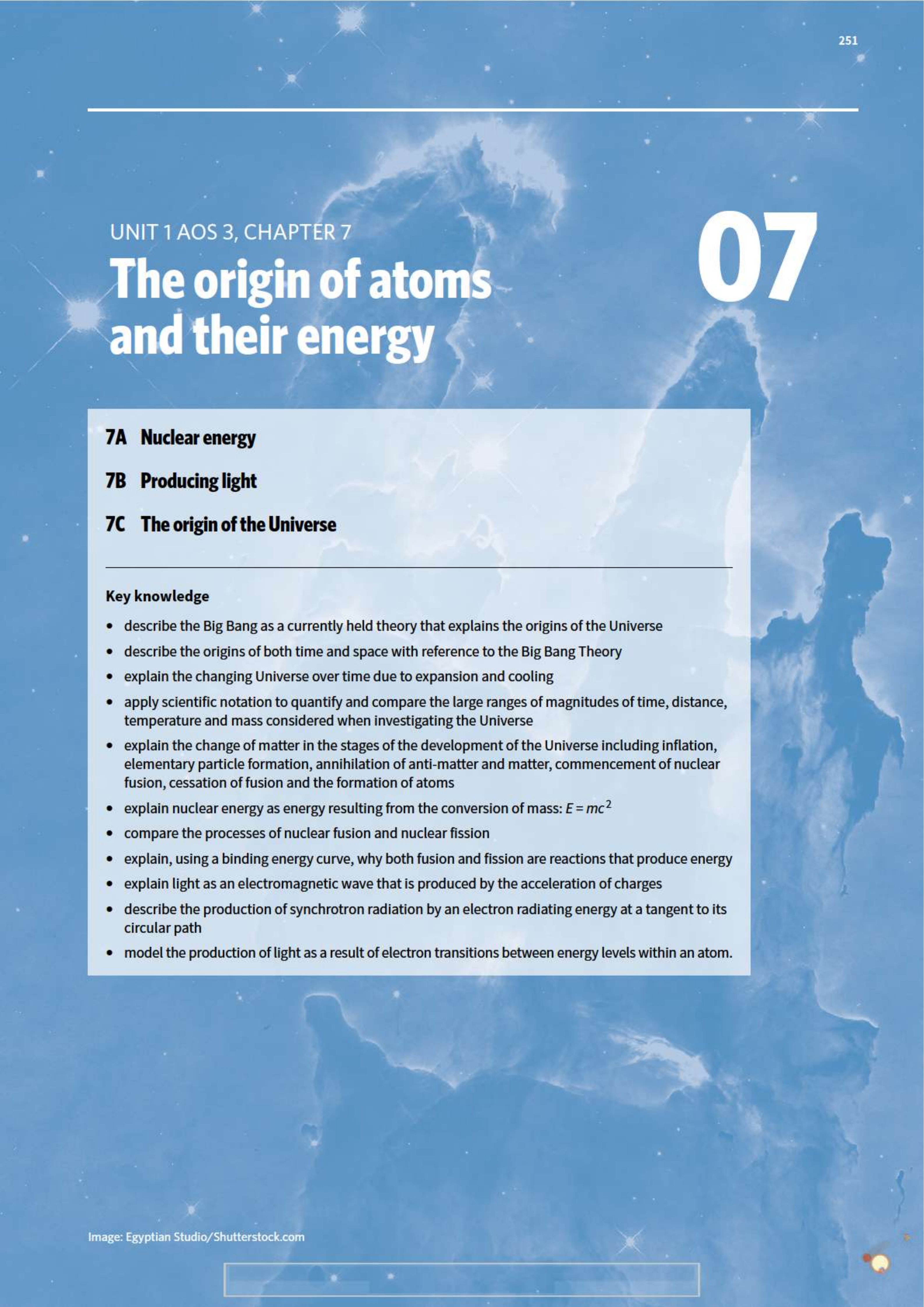
b $^{218}_{85}At \rightarrow ^{?}_{83}Bi + \ldots$ (2 MARKS)

Question 12 (2 MARKS)

In an experiment to determine the half-life of an isotope, measurements are made of the mass of the isotope present in a sample at intervals of 6 hours. At one time, the mass of the sample is 20 mg. At the next measurement, the mass is 5 mg. What is the half-life of the isotope?

Question 13 (4 MARKS)

The activity of a sample at 12 PM is 1600 Bq. The activity of the sample decreases to 200 Bq by 6 PM on the same day. What will the activity be at 10 PM?



UNIT 1 AOS 3, CHAPTER 7

The origin of atoms and their energy

07

Key knowledge

- describe the Big Bang as a currently held theory that explains the origins of the Universe
- describe the origins of both time and space with reference to the Big Bang Theory
- explain the changing Universe over time due to expansion and cooling
- apply scientific notation to quantify and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the Universe
- explain the change of matter in the stages of the development of the Universe including inflation, elementary particle formation, annihilation of anti-matter and matter, commencement of nuclear fusion, cessation of fusion and the formation of atoms
- explain nuclear energy as energy resulting from the conversion of mass: $E = mc^2$
- compare the processes of nuclear fusion and nuclear fission
- explain, using a binding energy curve, why both fusion and fission are reactions that produce energy
- explain light as an electromagnetic wave that is produced by the acceleration of charges
- describe the production of synchrotron radiation by an electron radiating energy at a tangent to its circular path
- model the production of light as a result of electron transitions between energy levels within an atom.

Image: Egyptian Studio/Shutterstock.com

7A NUCLEAR ENERGY

Energy and mass are in fact equivalent and are linked by perhaps the most famous equation in physics, $E = mc^2$. This relationship suggests that a tremendous amount of energy could be released from the conversion of a small amount of mass. This lesson will explore this mass-energy equivalence and how it underpins the processes of nuclear fusion and fission. It will also introduce the concept of binding energy, and explore how both fusion and fission can release energy.

7A Nuclear energy	7B Producing light	7C The origin of the Universe

Study design dot points

- explain nuclear energy as energy resulting from the conversion of mass: $E = mc^2$
- compare the processes of nuclear fusion and nuclear fission
- explain, using a binding energy curve, why both fusion and fission are reactions that produce energy

Key knowledge units

Mass-energy equivalence	1.3.17.1
Nuclear fusion and nuclear fission	1.3.18.1
Binding energy curves	1.3.19.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$E = mc^2$ mass-energy equivalence
	$\Delta E = \Delta mc^2$ conversion of mass-energy

Definitions for this lesson

binding energy the total energy required to split a nucleus into its constituent nucleons

mass defect the difference in mass between a nucleus and its constituent nucleons

nuclear fission the process of splitting a single nucleus into several smaller nuclei

nuclear fusion the process of forcing several smaller nuclei together to form a single large nucleus

product a substance that is formed as the result of a reaction

reactant a substance present at the start of a reaction and is involved in the reaction

Mass-energy equivalence 1.3.17.1

OVERVIEW

Mass and energy are equivalent to each other and are related by $E = mc^2$.

THEORY DETAILS

Anything with mass has an intrinsic energy proportional to its mass. This equivalence between mass and energy was proposed by Einstein as a consequence of his theory of relativity. This mass-energy equivalence is described by the following equation.

$$E = mc^2$$

E = energy (J), m = mass (kg), c = speed of light (3.0×10^8 m s^{-1})

The presence of the c^2 term in this mass-energy relationship reveals that there is a tremendous amount of energy contained in small amounts of mass. If a single gram of matter is converted entirely into energy, it would release 9×10^{13} J, or enough energy to power 4000 homes for a year.

This equivalent energy, known as the rest energy, is nearly always "trapped" as matter. However, this stored energy can be released or added to in nuclear reactions. If the sum of the masses of the reactants (mass before the reaction) is different to the sum of the masses of the products (mass after the reaction), mass must have been converted to energy or energy converted to mass. We can calculate these changes by using a manipulated form of the mass-energy equivalence formula.

$$\Delta E = \Delta mc^2$$

ΔE = change in energy (J), Δm = change in mass (kg), c = speed of light (3.0×10^8 m s^{-1})

The most fundamental example of matter being converted to energy is the formation of atoms. The nucleus of an atom will be lighter (less massive) than the total mass of the protons and neutrons that form the nucleus.

This difference in mass is known as the mass defect and represents the energy released when the bonds in the nucleus are formed.

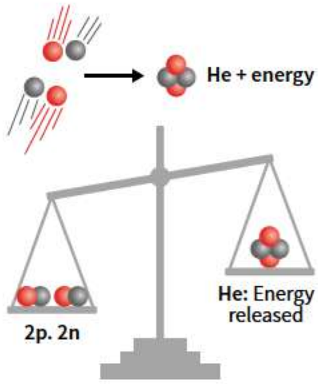


Figure 1 A nucleus is lighter than the nucleons that it is composed of. This difference in mass is released as energy.

Worked example 1

The nucleus of the carbon-12 isotope contains 6 protons and 6 neutrons. Use the provided data to

a calculate the mass defect in forming one carbon-12 nucleus.

b calculate how much energy was released in forming one carbon-12 nucleus.

Mass of carbon-12 nucleus = $1.9923774 \times 10^{-26}$ kg

Mass of proton = $1.6726219 \times 10^{-27}$ kg

Mass of neutron = $1.6749275 \times 10^{-27}$ kg

Working	Process of thinking
a $6 \times 1.6726219 \times 10^{-27} + 6 \times 1.6749275 \times 10^{-27}$ $= 2.00853 \times 10^{-26}$ kg	Calculate the mass of all the subatomic particles that form the carbon-12 atom. The nucleus contains 6 protons and 6 neutrons, given in the question.
$\Delta m = 2.00853 \times 10^{-26} - 1.9923774 \times 10^{-26}$ $= 1.61526 \times 10^{-28}$ kg The mass defect is 1.61526×10^{-28} kg	Find the difference between the mass of carbon-12 and the sum of the masses of the components.
b $\Delta E = \Delta mc^2$ $\Delta E = 1.61526 \times 10^{-28} \times (3.0 \times 10^8)^2$ $\Delta E = 1.454 \times 10^{-11}$ J 1.5×10^{-11} J of energy is released	Use the conversion of mass-energy equation to find the energy released in the formation of the atom. From part **a**, $\Delta m = 1.61526 \times 10^{-28}$ kg

Nuclear fusion and nuclear fission 1.3.18.1

OVERVIEW

Nuclear fusion and fission are both processes that change atomic nuclei into different nuclei. Both processes typically lead to a decrease in mass and release energy in the process.

THEORY DETAILS

Nuclear fusion and fission are examples of nuclear reactions which result in products that are different elements from the reactants. Nuclear reactions will never make or destroy nucleons and hence the number of nucleons in the products will be identical to the number of nucleons in the reactants. Hence the atomic and mass numbers of an unknown nucleus in a reaction can be identified, using the same methods as in Lesson 6D. Both fusion and fission reactions result in products that are less massive than the reactants and will release energy.

Fusion

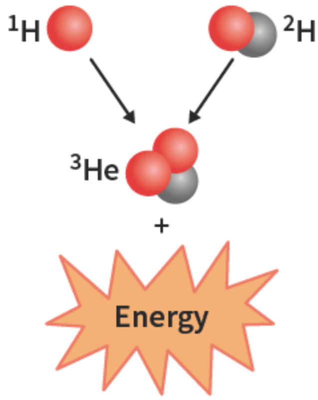


Figure 2 The fusion of two hydrogen isotopes to form a helium nucleus, releasing energy

Nuclear fusion is a reaction that involves combining (or fusing) two lighter nuclei into a single heavier nucleus. For such a reaction to occur, the reactant nuclei must be forced extremely close together in order to overcome the electrostatic forces repelling the positively charged nuclei. When the resulting nucleus has less mass than the sum of the masses of the nuclei that were fused to form it, this mass difference is released as energy, which we can calculate using $\Delta E = \Delta mc^2$.

Fusion reactions occur continuously within stars including the Sun, releasing the energy that powers them. For most of the life of the star, these reactions will be the fusion of hydrogen into helium. Since the Sun is releasing energy, it is actually losing mass over time – approximately 1.89×10^{17} kg per year.

As the abundance of hydrogen within a star decreases, it will continue to fuel itself through the fusion of increasingly heavy elements, which become increasingly less efficient as the elements get heavier.

Starting a fusion reaction requires the nuclei to be forced together close enough for the strong force to overcome the electrostatic repulsion. Doing so typically requires extremely energetic conditions, meaning very high temperatures or an immense pressure, or more commonly a combination of both. For example, the core of the Sun, where the fusion reactions take place, has a temperature of 1.57×10^7 K and a pressure of roughly 2.7×10^{11} times that of the air on the surface of Earth.

Worked example 2

The fusion of hydrogen nuclei into a helium nucleus is given by the following equation:

$^2_1H + ^1_1H \rightarrow ^3_2He$ + energy

Use the following data to calculate how much energy is released.

Mass of $^1_1H = 1.67262 \times 10^{-27}$ kg

Mass of $^2_1H = 3.34359 \times 10^{-27}$ kg

Mass of $^3_2He = 5.00824 \times 10^{-27}$ kg

Working	Process of thinking
$\Delta m = 5.00824 \times 10^{-27} - 3.34359 \times 10^{-27} - 1.67262 \times 10^{-27}$ $\Delta m = -7.97 \times 10^{-30}$ kg	Find the difference in mass between the reactants and product.
$\Delta E = \Delta mc^2$ $\Delta E = -7.97 \times 10^{-30} \times (3.0 \times 10^8)^2 = -7.17 \times 10^{-13}$ J 7.2×10^{-13} J of energy is released.	Use $\Delta E = \Delta mc^2$ to find the equivalent energy released in the reaction.

Fission

Nuclear fission is the process of splitting a nucleus into two or more smaller nuclei. The fission of a stable atom requires an initial input of energy to overcome the strong force binding the nucleus together. After this input of energy, the electrostatic force repelling the protons is the dominant force and the nucleus splits into two or more smaller nuclei.

The most common mechanism to begin a nuclear fission reaction is to bombard a heavy nucleus with neutrons which supply the initial energy required to overcome the strong force. The nucleus will 'capture' the neutron and the additional energy will force the nucleus apart enough for the electrostatic repulsion to overcome the strong force and hence the nucleus will split.

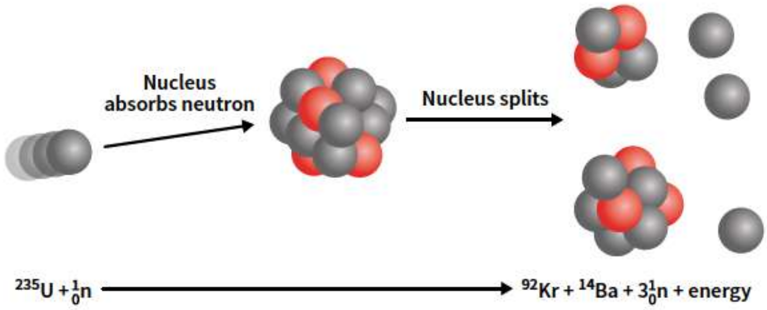


Figure 3 Uranium-235 capturing a neutron before undergoing fission and splitting into two smaller nuclei as well as three neutrons. Energy is released in the process.

Nearly all fission reactions will result in two product nuclei, typically of slightly different sizes, but occasionally can produce three or more nuclei. Often fission reactions will produce free neutrons, which can then go on to trigger other fission reactions. This chain reaction is the process that allows nuclear reactors to continue running.

Unlike nuclear fusion, the necessary conditions for fission are easily achievable on Earth. This allows nuclear fission to be controlled and harnessed for the production of electricity in nuclear power plants.

Binding energy curves 1.3.19.1

OVERVIEW

The binding energy of a nucleus is the energy required to break a nucleus into its constituent neutrons and protons. The binding energy curve shows that the number of nucleons in a nucleus will affect how tightly bound it is.

THEORY DETAILS

For a stable atom to be completely separated into unbound nucleons, we must add energy to the nucleus to overcome the strong nuclear force holding the nucleus together. The more tightly bound the nucleus, the more energy must be added. This energy is known as the binding energy and it is the energy equivalent to the mass defect in the formation of the atom. Since a bonded nucleus will always be lighter than its component nucleons, the binding energy will always be positive.

A binding energy curve graphs the binding energy of nuclei against the number of nucleons within the nucleus. As shown in Figure 4, the vertical axis will typically show the binding energy per nucleon, rather than the total binding energy.

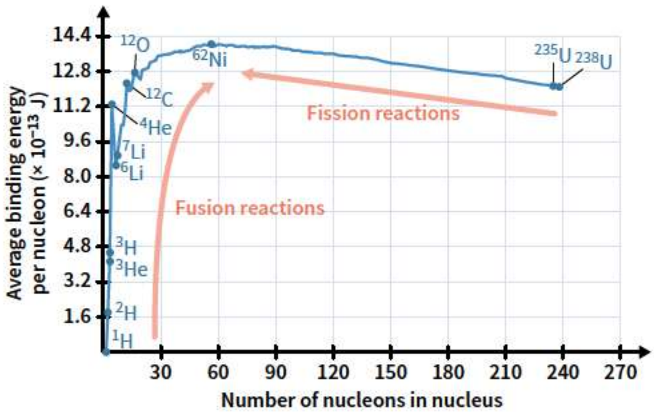


Figure 4 Binding energy curve, showing the binding energy per nucleon versus the number of nucleons. Nickel-62 has the highest binding energy per nucleon.

The binding energy curve begins at ^{1}H which is simply a single proton which has zero binding energy. As the nucleus increases its nucleon count, the strong nuclear force and the electrostatic repulsion both increase. Initially the strong force increases more per nucleon than the electrostatic force, so the nucleus becomes more tightly bound together, and hence the binding energy increases. At nickel-62, the binding energy curve peaks which represents the most tightly bound nucleus and hence the greatest binding energy per nucleon. As the nuclei gets even larger, the electrostatic repulsion increases faster than the attractive strong force. Consequently, the binding energy per nucleon begins to fall.

Although nickel-62 has the highest binding energy per nucleon, iron-56 has the least average mass per nucleon, due to a higher ratio of protons to neutrons. Consequently, the decay of Ni-62 to Fe-56 could release energy as a result of the beta decay of neutrons into slightly lighter protons, but this could not occur as a result of fusion or fission reactions.

The difference in total binding energy between the reactants and the products is equal to the energy released in the reaction. Any reaction in which the products have a greater binding energy than the reactants will release energy.

This means that both nuclear fusion and fission can release energy.

- For **small** nuclei (to the left of nickel on the binding energy curve), a **fusion** reaction (which results in a product to the right of the reactants) would increase the binding energy per nucleon and release this difference in energy to the surrounding environment.
- For **larger** nuclei (to the right of nickel on the binding energy curve), a **fission** reaction (which results in products to the left of the reactant) would produce more tightly bound products, which would also release energy to the environment.

Theory summary

- Nuclear energy is released from the conversion of mass, following Einstein's famous equation $E = mc^2$.
- Mass defect is the difference between the mass of an atom and the sum of the mass of its constituent parts. It represents the energy released to form the atom, and is equivalent to the nuclear binding energy.
- Nuclear fusion involves forcing light nuclei to combine into a single larger nucleus, typically requiring immense temperatures and pressures. This process leads to a decrease in mass and a release of energy.
- Nuclear fission involves splitting a larger nucleus into smaller nuclei, during which the mass decreases and energy is released.
- The binding energy of a nucleus is a measure of how tightly bound that nucleus is.
- A binding energy curve shows the binding energy per nucleon versus the number of nucleons in the atom.
  - If a nuclear reaction results in energy being released, the products must have a higher position on the binding energy curve.
  - A fusion reaction will have products to the right of the reactants.
  - A fission reaction will have products to the left of the reactants.

KEEN TO INVESTIGATE?

YouTube video: Bozeman Science – Nuclear Reactions
youtu.be/50RWvXmQcFk

YouTube video: SciShow – Why Don't We Have Nuclear Fusion Power Yet?
youtu.be/riOvBEEs9WY

CONCEPT DISCUSSION QUESTION

Stars are fuelled by the fusion of nuclei within their cores. As stars age, they burn increasingly heavy fuel until around iron and nickel at the end of its life. The formation of nuclei that are more massive than nickel requires cataclysmic events, such as supernovae or merging neutron stars.

Discuss why stars produce heavier elements as they age, but only up to around iron and nickel. Also consider why producing elements heavier than those found in stars require the most energy intense environments in the Universe.

Answers on page 506

Hints

Why would stars preferentially burn hydrogen until it is exhausted before moving on to increasingly heavier elements?

What is special about the nuclei of elements such as iron and nickel, which would explain why stars do not produce heavier elements?

How does the energy released in nuclear fusion change once the nuclei get bigger than nickel?

7A Questions

THEORY REVIEW QUESTIONS

Question 1

For each of the following statements, state whether it applies to nuclear fusion, nuclear fission or both.

- **a** The number of nucleons remains unchanged.
- **b** Small nuclei are forced together, forming a single heavier one.
- **c** There is a net energy release.
- **d** A large nucleus is split into several smaller ones.
- **e** The products are lighter than the reactants.
- **f** The reaction is the source of energy for stars.
- **g** The binding energy is greater after the reaction.
- **h** The reaction can be harnessed for efficient energy generation.

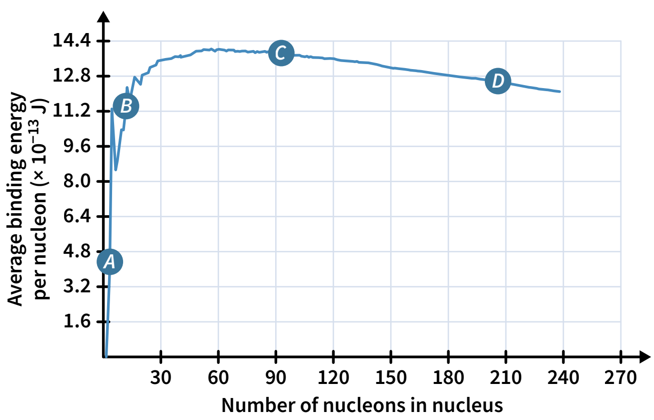
Question 2

What is the value of x in the following reaction? (How many neutrons are released as products in this reaction?)

$^{237}_{93}\text{Np} + ^{1}_{0}n \rightarrow ^{159}_{63}\text{Eu} + ^{72}_{28}\text{Ni} + ^{4}_{2}\text{He} + x^{1}_{0}n$

- **A** 1
- **B** 2
- **C** 3
- **D** 4

Use the following graph to answer Questions 3–5. The points A to D represent different isotopes on the binding energy curve.



Question 3

Which of the isotopes would you expect to release the most energy per nucleon when undergoing nuclear fusion?

Question 4

Which of the isotopes would you expect to release the most energy per nucleon when undergoing nuclear fission?

Question 5

Which of the isotopes would you expect to have the most tightly bound nucleus?

Question 6

Fill in the blanks to correctly describe the processes of nuclear fusion and fission.

Nuclear __________ (fusion/fission) is the process of several smaller nuclei being forced together and forming a new, __________ (smaller/larger) nucleus. This requires an __________ (intense/minimal) pressure or temperature environment and will typically have a net energy __________ (release/loss). Nuclear __________ (fusion/fission) is the process of splitting a larger nucleus into several smaller nuclei, leading to a net energy __________ (release/loss).

Question 7

The binding energy of a nucleus and its mass defect are equivalent and can be related by $\Delta E = \Delta mc^2$.

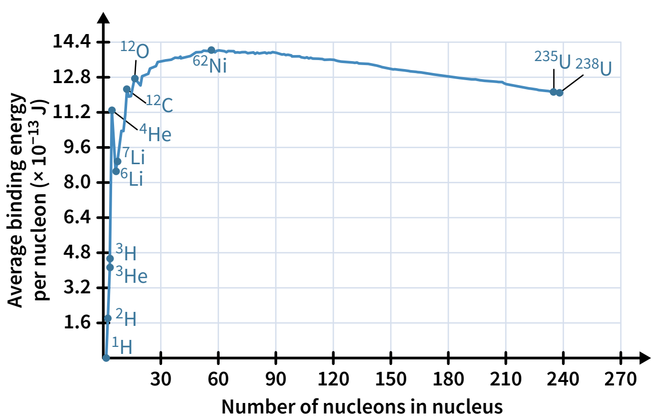
- **A** True
- **B** False

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (4 MARKS)

The following reaction occurs as part of the fusion of hydrogen to helium within stars larger than the Sun.

$^{12}_{6}\text{C} + ^{1}_{1}\text{H} \rightarrow ^{13}_{7}\text{N} + \textit{energy}$



Prompts

a What is the total binding energy of a carbon-12 nucleus?

A 1.23×10^{-12} J

B 7.39×10^{-12} J

C 1.48×10^{-11} J

D 12 J

b What is the total binding energy of a proton?

A -1.6×10^{-13} J

B 0 J

C 1.6×10^{-19} J

D 2.0×10^{-13} J

c What is the total binding energy of a nitrogen-13 nucleus?

A 0 J

B 1.20×10^{-12} J

C 7.39×10^{-12} J

D 1.51×10^{-11} J

Question

d Using the binding energy curve, determine how much energy is released in this fusion reaction. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (2 MARKS)

The mass defect in the formation of an $^{16}_{8}O$ nucleus is 2.202×10^{-28} kg. How much energy is released in the formation of this nucleus?

Question 10 (2 MARKS)

The following example of a nuclear reaction releases 2.06×10^{-13} J of energy. What is the difference in mass between the products and the reactants?

$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{2}_{4}He + 2^{1}_{1}H + \textit{energy}$

Question 11 (2 MARKS)

Nuclear fusion and nuclear fission are both examples of nuclear reactions that release energy. This energy release results from a difference in binding energy between the reactants and the products.

a How does the binding energy of the product of nuclear fusion compare to the binding energy of the reactant nuclei? (1 MARK)

b How does the binding energy of the products of nuclear fission compare to the binding energy of the reactant nucleus? (1 MARK)

Question 12 (3 MARKS)

A typical nuclear reactor will produce approximately 2.6×10^{5} GJ every day. This will be produced by the fission of 3.6 kg of uranium-235 fuel. What percentage of the mass of the fuel is converted to energy?

Question 13 (7 MARKS)

In the following reaction, 0.10% of the mass of the reactant was converted to energy.

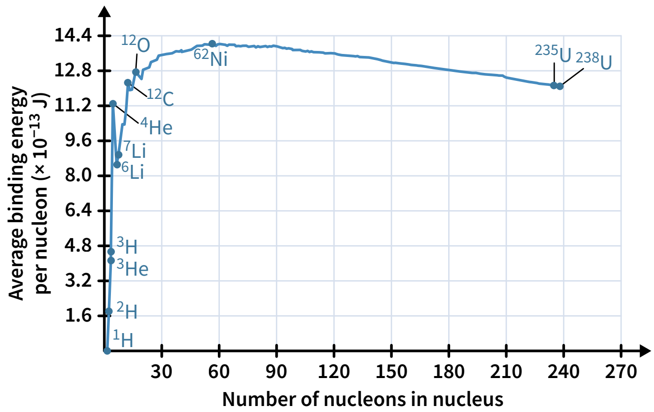
$X + ^{1}_{0}n \rightarrow ^{145}_{58}Ce + ^{91}_{36}Kr + 4^{1}_{0}n + \textit{energy}$

a How many protons and neutrons are there in the reactant, X? (3 MARKS)

b How much of the reactant is required to produce 1.0 TJ (1.0×10^{12} J) of energy? Give your answer in kilograms. (4 MARKS)

Question 14 (3 MARKS)

Using the binding energy curve, calculate the mass defect for iron-56.



Question 15 (4 MARKS)

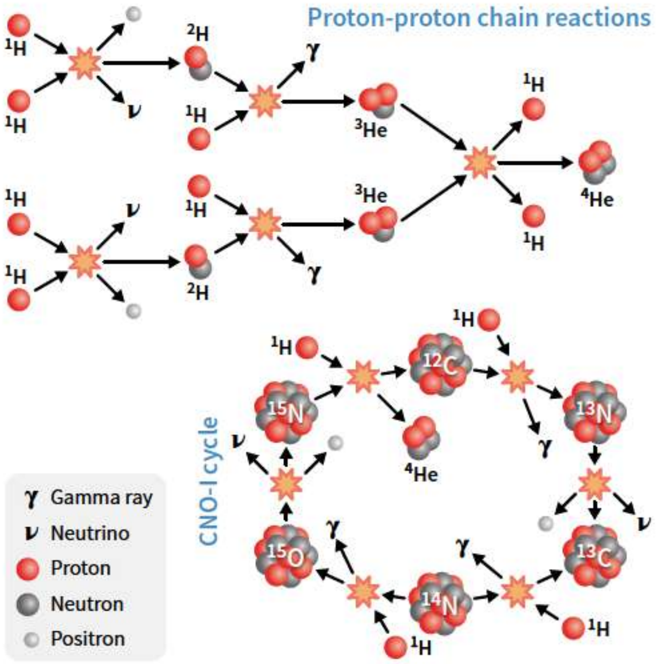
Both nuclear fusion and fission reactions release energy as a result of a difference in binding energy. Fusion reactions involve small nuclei while fission reactions can use a reactant an order of magnitude heavier.

a How does the energy released per nucleon differ between a single nuclear fusion reaction and a single nuclear fission reaction? (2 MARKS)

b How does the total energy released differ between a single nuclear fusion reaction and a single nuclear fission reaction? (2 MARKS)

Question 16 (2 MARKS)

All stars use the fusion of hydrogen into helium to release energy, but the reaction pathway will depend on the size of the star. Small stars use the proton-proton chain, while larger stars will predominantly use the CNO cycle. Both pathways have the same net reaction.



$4\,{}^{1}H^{+} \rightarrow {}^{4}He^{2+} + 2e^{+} + 2v_{e} + \textit{energy}$

How would you expect the energy released to compare between these two processes?

Previous lessons

Question 17 (3 MARKS)

Determine the amount of charge transferred by a 500 W jigsaw in 10 minutes, if it is connected to a 120 V power supply.

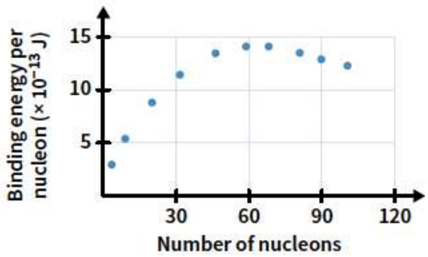
Question 18 (2 MARKS)

Would the iron isotope ${}^{52}_{26}Fe$ likely be stable or unstable? Justify your answer.

Key science skills

Question 19 (2 MARKS)

A group of students were investigating the relationship between the size of an atom and the average binding energy. They obtained the data points plotted in the following graph.



Advise the students whether it would be appropriate to fit a line of best fit to the data. Justify your response.

7B PRODUCING LIGHT

This lesson builds on our understanding of electromagnetic radiation that was introduced in Lesson 3A. We will explore how light can be created at incredible intensity in a synchrotron and at incredibly small scales through electrons transitioning between energy levels.

7A Nuclear energy	7B Producing light	7C The origin of the Universe

Study design dot points

- explain light as an electromagnetic wave that is produced by the acceleration of charges
- describe the production of synchrotron radiation by an electron radiating energy at a tangent to its circular path
- model the production of light as a result of electron transitions between energy levels within an atom

Key knowledge units

Light as an electromagnetic wave	1.3.20.1
Synchrotron radiation	1.3.21.1
Producing light from electron transitions	1.3.22.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$E_{released} = \Delta E$ energy released as electromagnetic radiation due to electron transitions

Definitions for this lesson

discrete limited to certain values (not continuous)

synchrotron a machine for accelerating charged particles to a great speed in order to release electromagnetic radiation

tangent a line which touches, but does not cross, a curve at a single point

Light as an electromagnetic wave 1.3.20.1

OVERVIEW

Light can be modelled as an electromagnetic wave comprised of oscillating perpendicular electric and magnetic fields. It is produced by the acceleration of charged particles. The speed of all electromagnetic waves in a vacuum is a constant.

THEORY DETAILS

A stationary charged particle has a constant electric field around it. When the particle is accelerating, this electric field produces a (perpendicular) changing magnetic field, which produces a changing electric field, and so on. The resulting oscillating fields are known as an electromagnetic wave or electromagnetic radiation. If a charged particle is oscillating, the frequency of the electromagnetic wave produced will be equal to the frequency of the oscillation.

Electromagnetic waves are unique in that they do not require a medium to travel in, meaning they can move through a vacuum. This is as they are made up of varying electric and magnetic fields which exist in vacuums.

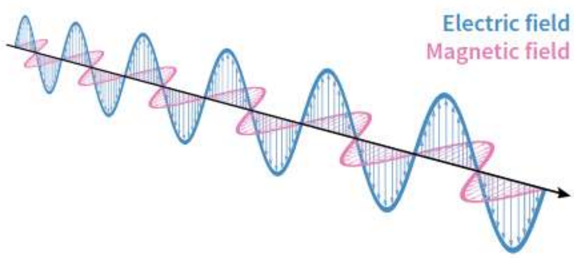


Figure 1 An electromagnetic wave. The oscillating electric and magnetic fields are perpendicular to each other.

All electromagnetic waves travel at the same speed in a vacuum, known as the speed of light, which is independent of frequency and wavelength. This speed is denoted by the symbol c which is equal to 3.0×10^8 m s^{-1} to two significant figures.

Recalling from Lesson 3A, visible light consists of a small range of frequencies of electromagnetic waves. However, the words 'light' and 'electromagnetic radiation' are used interchangeably in physics to describe radiation from any part of the electromagnetic spectrum.

Synchrotron radiation 1.3.21.1

OVERVIEW

Synchrotrons use the acceleration of charged particles travelling in a circle to generate electromagnetic radiation with extreme intensity at a tangent to its circular path.

THEORY DETAILS

A synchrotron produces light by accelerating charged particles, most commonly electrons and protons, around a circular 'storage ring' to near the speed of light. The particles are accelerated by utilising the electromagnetic force.

The constant changing of direction that a charged particle experiences as it travels around the synchrotron is a form of acceleration. Although the speed will be relatively constant, the velocity is changing due to the charged particle's change of direction. Therefore, the electron is accelerating and producing light. Light is emitted at a broad range of electromagnetic frequencies (from microwaves to X-rays), although specific frequencies can be isolated.

The light is emitted with extreme intensity in a direction which is tangential to the charged particle's path through small holes in the synchrotron's storage ring (see Figure 2). The tangent is a line that only touches a curve in a single spot and, in the case of a circle, is perpendicular to its radius.

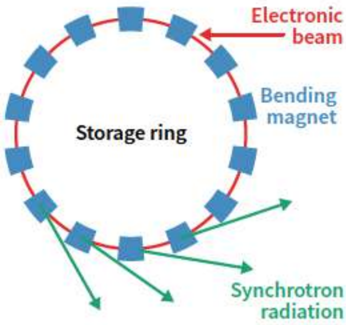


Figure 2 The red circle shows the path of charged particles in a synchrotron as they are accelerated by extremely strong bending magnets (the blue boxes). The green arrows represent resultant tangential light.

Imagine we are swinging a ball on the end of a rope in a circle (like the hammer throw Olympic sport). The tangent is the direction it would travel if we suddenly let go of the rope (see Figure 3). The tangent is also the direction of the ball's (or charged particle's) instantaneous velocity at that point.

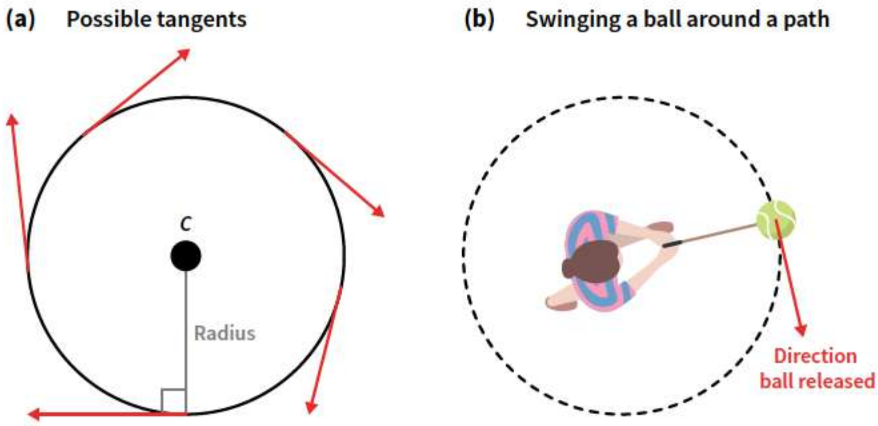


Figure 3 **(a)** Arrows represent some of the possible tangents to a circle. **(b)** This is the same direction a ball would travel if it were released at this point after being swung around in a circle.

Synchrotrons are large (the Australian Synchrotron located at Monash University in Clayton has a circumference of 216 m) and often contain expensive research facilities. The Australian Synchrotron contains two additional chambers specifically to accelerate the charged particles to the near-light-speeds required. These chambers are a linear accelerator (linac) and a booster chamber which lead into the storage ring. It is from the storage ring that the high-intensity radiation is released.

Producing light from electron transitions 1.3.22.1

OVERVIEW

Electrons exist in discrete energy levels around an atom. When electrons drop from a higher energy level to a lower energy level they emit electromagnetic radiation.

THEORY DETAILS

Electrons exist in an atom only in discrete energy levels (see Figure 4). Each energy level is represented by an integer value $n = 1, 2, 3...$ The lowest energy level ($n = 1$) is known as the ground state, and the other levels are the excited states.

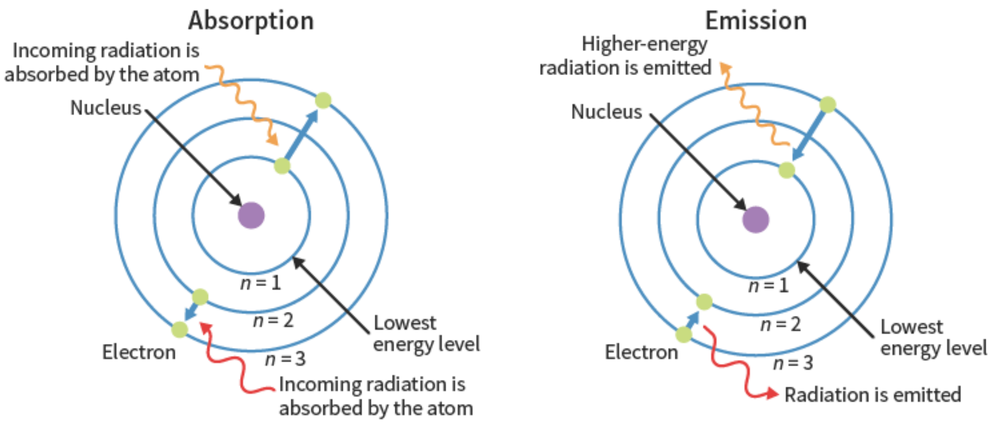


Figure 4 The increasing energy levels of an electron, represented by *n*

The electrons can transition between the energy levels by absorbing or emitting energy in the form of electromagnetic radiation. Since energy is conserved, the electromagnetic radiation's energy **must equal the difference between any two energy levels.** When an electron drops from a higher energy level to a lower energy level they emit radiation with energy equal to the difference in the energy levels.

The energy absorbed and emitted is very small, so we can use a new, smaller unit of energy when calculating the energy changes of subatomic particles. This is called an electron volt (eV).

$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$

$E_{released} = \Delta E$

$E_{released}$ = energy released electromagnetic radiation (eV or J), ΔE = change in energy between two energy levels (eV or J)

The energy of emitted electromagnetic radiation corresponds to particular frequencies (and wavelengths). This is because the energy of electromagnetic radiation is proportional to its frequency.

$E_{released} \propto f$ and $E_{released} \propto \frac{1}{\lambda}$

An electron **can transition between any two** energy levels. We use an arrow to indicate this on an energy level diagram. In Figure 5, the red arrow shows an energy transition from $n = 2$ to $n = 1$ by emitting electromagnetic radiation with an energy of 10.2 eV. The blue arrow shows an energy transition from $n = 1$ to $n = 3$ by absorbing electromagnetic radiation of 12.1 eV. The green arrow shows an energy transition from $n = 5$ to $n = 3$ by emitting electromagnetic radiation with an energy of 13.1 − 12.1 = 1.0 eV.

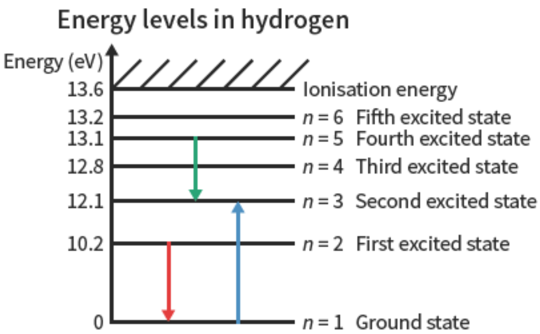


Figure 5 Electron energy levels in hydrogen. The arrows represent possible transitions between energy levels.

An electron in an excited state will rapidly move back to the ground state. In doing so it can take any available "path". For example, an electron at $n = 6$ could drop directly to $n = 1$, or it could drop to $n = 4$ to $n = 3$ and then to $n = 1$, or it could drop through every level before reaching the ground state.

Ionisation

The ionisation energy represents the energy an electron needs to be emitted from the atom. Any incident electromagnetic radiation with energy greater than or equal to the ionisation energy of an electron will emit an electron from the atom.

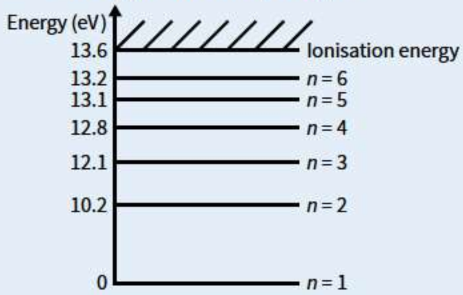
Worked example 1

An electron in a hydrogen atom changes energy states from $n = 6$ to $n = 3$.

a Is the electron emitting or absorbing electromagnetic radiation?

b What is the energy of the electromagnetic radiation?

Energy levels in hydrogen



Working	Process of thinking
a The electron will emit electromagnetic radiation.	The electron transitions from $n = 6$ to a lower energy state of $n = 3$, thus it loses energy and must emit it in the form of electromagnetic radiation.
b $E_{released} = \Delta E = E_6 - E_3$ $E_{released} = 13.2 - 12.1 = 1.1$ eV	From the graph we read $E_6 = 13.2$ eV, $E_3 = 12.1$ eV. Check the answer makes sense. The emitted energy should be positive energy.

Theory summary

- Light (any part of the electromagnetic spectrum) is produced by the acceleration of charged particles. This acceleration induces oscillating electric and magnetic fields that are perpendicular to each other and propagate at the speed of light.
- Synchrotrons produce light through accelerating large amounts of charged particles in a circular path.
  - Electromagnetic radiation is produced by the accelerating charged particles and are released at a tangent to their path.
  - This light is high intensity and is across a large range of the electromagnetic spectrum.
- Light is also emitted when electrons transition from higher to lower energy levels states in an atom.
  - Electrons exist in discrete energy levels around the nucleus.
  - The energy of emitted electromagnetic radiation is equal to the difference in energy levels.

KEEN TO INVESTIGATE?

oPhysics 'Hydrogen Atom: Energy Levels' simulation
ophysics.com/m1.html

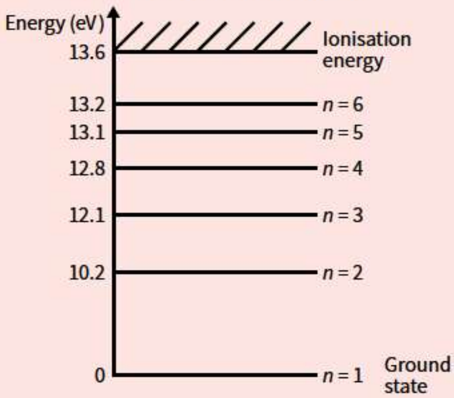
YouTube video: Diamondlightsource – What is the Diamond synchrotron?
youtu.be/4tpHZwsLB-Y

CONCEPT DISCUSSION QUESTION

Lasers use excited electrons to emit electromagnetic radiation. Lasers are particularly useful as the vast majority of the radiation they release is of a single wavelength of light. A device within the laser excites particular atoms with a discrete energy, which happens to be in their absorption spectra. When they drop down they release light through electron transitions.

Using the graph, discuss what amount of energy the atoms should be given in order to produce only a single wavelength of light. Include what might happen if a different amount of energy is absorbed by the atom.

Energy levels in hydrogen



Answers on pages 506–507

Hints

What is the energy of the light being released?

Does the energy of light correspond to one or multiple wavelengths?

For each energy level, how many options are there for the energy of released light?

7B Questions

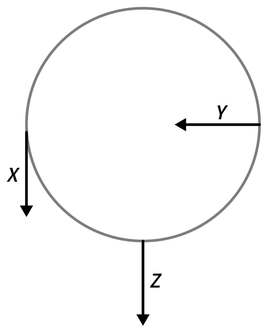
THEORY REVIEW QUESTIONS

Question 1

Fill in the gaps in the following paragraph.

Electromagnetic radiation is produced by the __________ (acceleration/motion) of charged particles. This produces a __________ (static/changing) electric field and an associated __________ (static/changing) magnetic field.

Use the following information to answer Questions 2 and 3.



Question 2

Which of the three arrows (*X*, *Y*, *Z*) represent a tangent to the circle?

A *X*

B *Y*

C *Z*

Question 3

Which of the three arrows (*X*, *Y*, *Z*) represent the direction in which electromagnetic radiation would be released at that point if the circle represents the charged particles' path in a synchrotron?

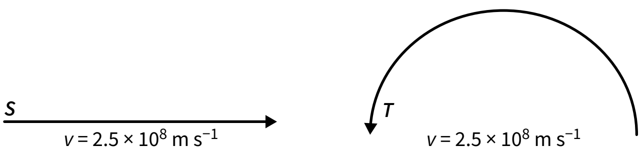
A *X*

B *Y*

C *Z*

Question 4

S and *T* are charged particles both moving at a constant speed of 2.5×10^8 m s^{-1}. *S* moves in a straight line and *T* moves in a circular path.



Select the particle(s) currently releasing electromagnetic radiation.

A *S*

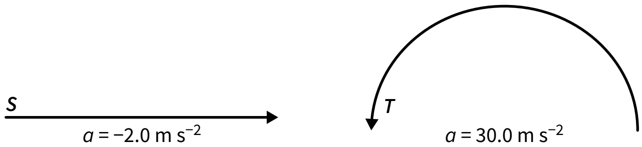
B *T*

C Neither

D Both

Question 5

S and *T* are charged particles both accelerating at different rates. *S* moves in a straight line and *T* moves in a circular path. Particle *S* is decelerating with a magnitude of 2.0 m s^{-2} and particle *T* is accelerating whilst travelling in a circle at a rate of 30.0 m s^{-2}.



Select the particle(s) currently releasing electromagnetic radiation.

A *S*

B *T*

C Neither

D Both

Question 6

Determine whether the following statement is true or false.

"Light is electromagnetic radiation."

A True

B False

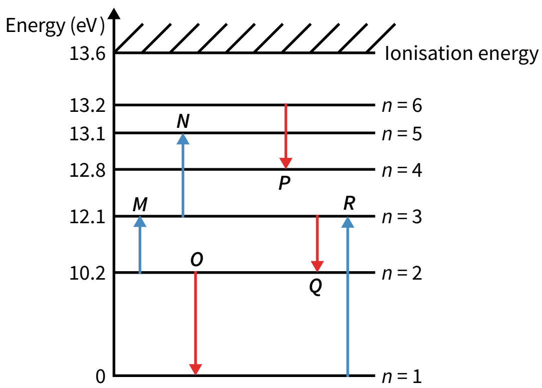
Question 7

Fill in the gaps in the following paragraph.

A synchrotron produces __________ (discrete/a continuous spectrum of) electromagnetic radiation through the acceleration of charged particles. Electrons transitioning between energy levels produces __________ (discrete/a continuous spectrum of) electromagnetic radiation.

Use the following diagram to answer Questions 8–11.

Energy levels in hydrogen



Question 8

Which two electron transitions in hydrogen correspond to an emission and absorption of electromagnetic radiation with the same energy?

A *M*, *N*

B *M*, *Q*

C *N*, *O*

D *N*, *R*

Question 9

Which electron transition is the result of the hydrogen atom absorbing electromagnetic radiation with an energy of 1 eV?

A *M*

B *N*

C *Q*

D *R*

Question 10

Which of the following transitions are a result of an electron absorbing electromagnetic radiation? *(Select all that apply)*

I *M*

II *N*

III *O*

IV *P*

V *Q*

VI *R*

Question 11

Which of the following lists only transitions that are a result of an electron emitting electromagnetic radiation? *(Select all that apply)*

I *M*

II *N*

III *O*

IV *P*

V *Q*

VI *R*

DECONSTRUCTED EXAM-STYLE QUESTION

Question 12 (3 MARKS)

A classmate announces that "all electromagnetic radiation is the result of the acceleration of charged particles".

Prompts

a Which of the following sources of electromagnetic radiation is **not** from the acceleration of charged particles?

- **A** Thermal radiation of a liquid or gas
- **B** Thermal radiation of a solid
- **C** Electrons changing energy levels
- **D** Synchrotron radiation

b Emission of electromagnetic radiation can occur through the acceleration of electrons and

- **A** the acceleration of any particle.
- **B** the cooling of hot materials.
- **C** the release of energy as electrons change from a lower to a higher energy level.
- **D** the release of energy as electrons change from a higher to a lower energy level.

Question

c Evaluate the classmate's statement. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 13 (1 MARK)

Which one of the following is the **best** reason that atoms only emit a certain set of wavelengths?

A As an atom only absorbs particular wavelengths it must also emit particular wavelengths.

B When electrons change states, they can only do so between discrete energy levels. This means there are only a certain set of wavelengths possible to be released.

C Electrons can only travel at discrete speeds, therefore the light emitted by electrons can only take certain values.

D This is not true. Electron transitions produce light across the entire electromagnetic spectrum.

Question 14 (3 MARKS)

In the storage ring of a particular synchrotron, electrons travel at a constant speed near the speed of light.

a Identify the direction that electromagnetic radiation is released by this synchrotron. (1 MARK)

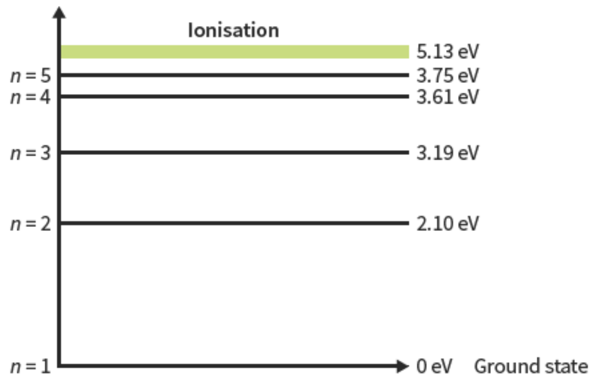
b Bending magnets surround the storage ring. Identify the force that accelerates the electrons and explain how the electrons are accelerating if they are not changing speed. (2 MARKS)

Question 15 (2 MARKS)

Explain how light is produced through the motion of charged particles.

Question 16 (7 MARKS)

Below is a diagram of the possible electron energy levels in a sodium atom.



a A sodium atom is excited to the $n = 3$ energy level.

List all the possible energies of electromagnetic radiation that it could emit as it returns to the ground state. (3 MARKS)

Adapted from 2016 VCAA Exam Section A Q21c

b On a copy of the energy-level diagram provided, draw an arrow to demonstrate the atomic energy level transition resulting from the emission of 1.51 eV of radiation. (2 MARKS)

Adapted from 2017 VCAA Exam Section B Q18a

c A student reports observing electronic radiation with an energy of 2.2 eV emitted from the atom. Is this possible? Explain your answer. (2 MARKS)

Question 17 (3 MARKS)

Explain how light is produced in a synchrotron.

Question 18 (3 MARKS)

Explain how light is produced through electron transitions in an atom.

Previous lessons

Question 19 (2 MARKS)

A 40 V battery operates on a series circuit with two resistors. The resistors have a resistance of 12 Ω and 50 Ω respectively. Calculate the current in the circuit when it is switched on.

Question 20 (2 MARKS)

Cobalt-60 is a commonly used source of radiation and has a half life of 5.27 years. Calculate how much of an 8.0 kg sample will remain after 31.62 years.

Key science skills

Question 21 (5 MARKS)

Emma and George are independently measuring wavelengths of light emitted from hydrogen due to electron transitions.

Emma's measurements of a particular transition are: 134 nm, 130 nm, 137 nm (average 134 nm).

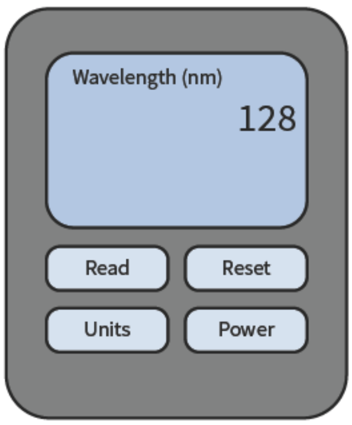
George's measurements of the same transition are: 126 nm, 140 nm, 127 nm (average 131 nm).

The wavelength of light for the transition is known to be at 132 nm.

a Whose results were more precise? Justify your answer. (2 MARKS)

b Whose results were more accurate? Justify your answer. (2 MARKS)

c Emma's readings were taken on this spectrometer. Determine the absolute uncertainty in her measurements. (1 MARK)



7C THE ORIGIN OF THE UNIVERSE

The observable Universe currently exists on scales that are nearly incomprehensible, however it began incomprehensibly small. This lesson will explore how the Universe has developed as explained by the Big Bang Theory, including the periods of expansion and cooling and how this led to the Universe we can see today.

7A Nuclear energy	7B Producing light	7C The origin of the Universe

Study design dot points

- describe the Big Bang as a currently held theory that explains the origins of the Universe
- describe the origins of both time and space with reference to the Big Bang Theory
- explain the changing Universe over time due to expansion and cooling
- apply scientific notation to quantify and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the Universe
- explain the change of matter in the stages of the development of the Universe including inflation, elementary particle formation, annihilation of anti-matter and matter, commencement of nuclear fusion, cessation of fusion and the formation of atoms

Key knowledge units

The Big Bang Theory	1.3.1.1 & 1.3.2.1 & 1.3.4.1
An expanding and evolving universe	1.3.3.1 & 1.3.5.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$v = H_0 d$ Hubble's law

Definitions for this lesson

inflation a very short time in which the early Universe underwent extremely rapid expansion

recessional velocity the rate at which an astronomical object is moving away from an observer

redshift where electromagnetic waves undergo an increase in wavelength

The Big Bang Theory 1.3.1.1 & 1.3.2.1 & 1.3.4.1

OVERVIEW

The Big Bang Theory is the currently held theory that describes the very early Universe and how it has evolved into what we can see today. The early Universe was characterised by its extreme temperature and density, which determined the formation and structure of the Universe that evolved from it.

THEORY DETAILS

The Big Bang Theory is a model that describes the earliest moments of the Universe and how it has evolved over 13.8 billion years (much like the animation in the corner of these pages has depicted). While the size of the entire Universe at any point in time is unknown, it is known that at a finite time in the past, the observable Universe had an extremely high density and temperature as it was concentrated in an incredibly small volume of space.

Many of the numbers in this lesson will be too large or small to comprehend. But we can put most of them into context by making comparisons using scientific notation (covered in Lesson 1B). For example, our galaxy has a radius of 5.0×10^{20} m, and the solar system has a radius of 1.4×10^{16} m. Taking the difference in their orders of magnitude (the values of their powers of 10 when written in scientific notation), we can say that our galaxy is approximately the width of $10^{20-16} = 10^4 = 10\ 000$ solar systems.

Timeline of the early Universe

The Universe in its earliest moments was very different to the Universe around us today. It was characterised by an extremely high temperature and density where the creation of elementary particles occurred.

As the Universe expanded, it became less dense and cooled. This allowed for the combination of elementary particles, eventually forming the matter around us today.

0–10^{-43} seconds – The Planck epoch

- Scientists have a very limited understanding of this earliest stage of the Big Bang – no current theory is able to describe such extreme conditions.
  - It is believed that the four fundamental forces – gravity, electromagnetism, the weak force, and the strong force – were a single unified force in this time.

10^{-43} seconds – The grand unification epoch

- The Universe enters a state governed by the laws of physics as we know them.
  - From this moment, time and space now have physical meaning.
- The temperature at this point is 140 million million million million million Kelvin (1.4×10^{32} K).

10^{-36}–10^{-32} seconds – The inflationary epoch

- During this period the Universe rapidly expanded (inflation), faster than the speed of light.
  - The volume of the Universe increases by a factor of at least 10^{78} – this level of expansion would expand the width of a human hair to the width of our galaxy.
- The Universe continues to expand after inflation, but at a much slower rate.

10^{-12}–10^{-6} seconds – The quark epoch

- The temperature is now low enough for the four fundamental forces to have separated from the single unified force.
- Elementary particles such as quarks are able to form, converting energy into matching particle-antiparticle pairs. These new particles are constantly being formed, but quickly collide due to the high density, annihilating back into energy (as in Figure 1).
  - At some point, an unknown process (or processes) results in a slight excess of matter over antimatter, which we can observe today.

10^{-6}–10^{0} seconds – The hadron epoch

- After 10^{-6} seconds, the Universe was too cold for new quarks to form, and the remaining quarks combined to form baryons.
- Particle-antiparticle pairs continue to annihilate, leaving only a small excess of matter. This matter contains a near-equal number of protons and electrons and is the matter that makes up everything in the Universe today.
- After 1 second, it was too cold for new leptons to form.

10 seconds – 20 minutes – Big Bang nucleosynthesis

- The Universe is now cool enough for atomic nuclei to form without being immediately broken apart, but still hot and dense enough for nuclear fusion to occur.
  - Approximately 25% of the protons (hydrogen-1) in the Universe fuse to form hydrogen-2 and most of that then fuses to form helium-4.
  - Some slightly heavier elements are formed as well, up to lithium-7. However, it would take billions of years and the formation of stars before other elements are present in the Universe.

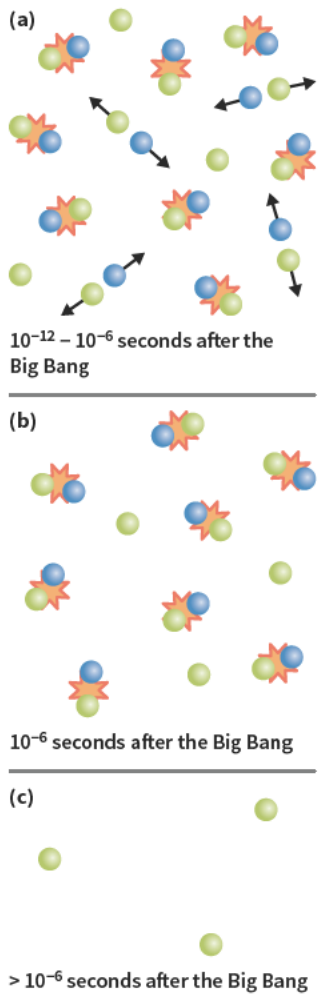


Figure 1 **(a)** Matter (green) and antimatter (blue) constantly formed and annihilated in pairs during the quark epoch (10^{-12}–10^{-6} seconds after the Big Bang). **(b)** When the Universe was too cool for matter/antimatter pairs to form, they continued to annihilate, leaving **(c)** a small excess of matter. Note that the proportion of matter left over was far smaller than depicted here.

370 000 years – Recombination

- The Universe has cooled sufficiently for electrons to orbit atomic nuclei and form the first neutral atoms.
  - Before neutral atoms were formed, the isolated electrons and nuclei formed an opaque plasma. With these particles combining, the light emitted is the first that is able to travel long distances.
  - A large amount of black body radiation is produced during this process. Its spectrum matches that emitted by a black body at 3000 K, the temperature of the Universe at the time.

An expanding and evolving universe 1.3.3.1 & 1.3.5.1

OVERVIEW

As the Universe continued to expand, matter began to take the shape of planets, stars and galaxies. By making observations about the Universe as it is today, we can verify the predictions of Big Bang Theory as the Universe once was.

THEORY DETAILS

The dark ages

The near-uniform density of the early Universe made the conditions for stars to be born a slow process, as minutely heavier regions pulled surrounding gases towards them under the effects of gravity over a period of hundreds of millions of years.

Matter continued to draw itself together under the influence of gravity, giving rise to galaxies, stars and black holes. Until these early stars were formed, little light could be produced.

The Universe as we know it

As the Universe was lit up by the light of early stars, it began to develop into what we see today. The nuclear fusion in stars' cores generates a huge range of elements (including ones heavier than lithium-7). Additionally, these early stars were quite different to most stars in the Universe today, typically massive blue stars with short lifetimes. They commonly exploded in supernovae, ejecting the newly-formed heavy elements into space (and also creating more elements in the process). This matter would go on to form new stars and planets.

About 8.8 billions years ago, the thin disk of the Milky Way (our galaxy) began to form. Roughly 4.6 billion years ago, the solar system was formed when a cloud of gas slowly collapsed under gravity. Most of the mass went to forming the Sun, and the rest into the bodies (planets, asteroids, etc.) that orbit it to this day.

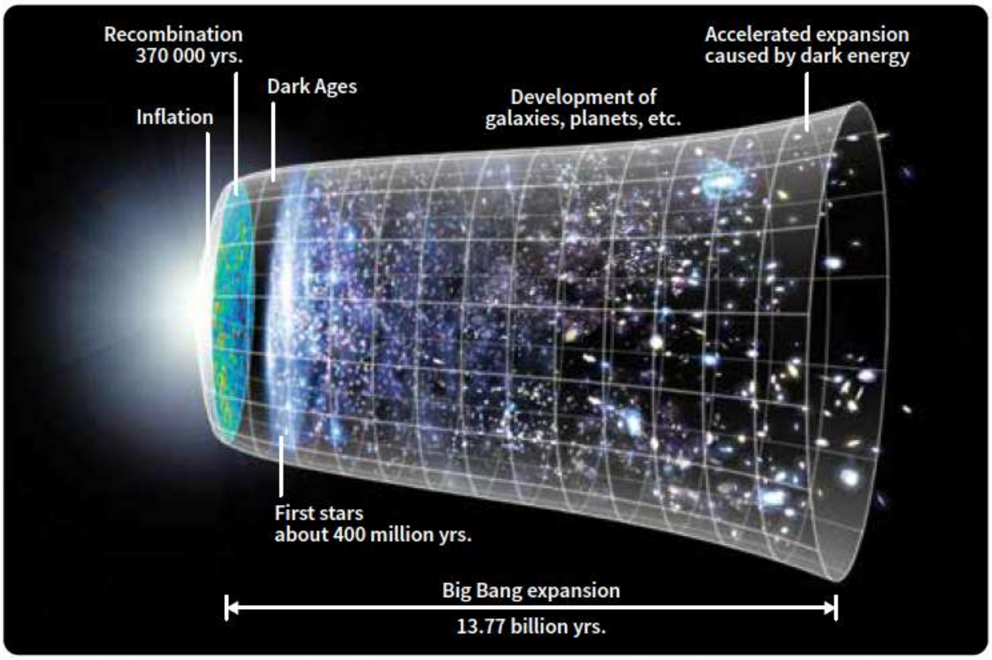


Figure 2 A depiction of the Universe's expansion

As the Universe has expanded, the rate of this expansion has changed.

- For around 9 billion years after the inflationary epoch, the Universe was still expanding, but bodies' recessional velocities were slowing, being "braked" by the effects of gravity.
- Then, around 5 billion years ago, the recessional velocities began to increase.
  - The Universe continues to expand more quickly than before.
  - There are various proposed hypotheses to explain this 'accelerating expansion' but it is something scientists are still trying to understand.

Modelling the expansion of the Universe

It can be helpful to think of the expansion of the Universe through an analogy. Suppose we have a partially inflated balloon with ants standing on its surface. The ants represent objects within the Universe such as stars – the ants' "universe" is only the two-dimensional surface, there is nothing above or below the surface. If we inflate the balloon, the space along the balloon's surface between the ants expands uniformly in all directions. From the perspective of any of the ants, all of the other ants are rushing away from it, but it is because the surface itself is expanding, rather than the ants walking along the surface. Further, there is no point on the surface of the balloon that the expansion is centred on, it is occurring everywhere.

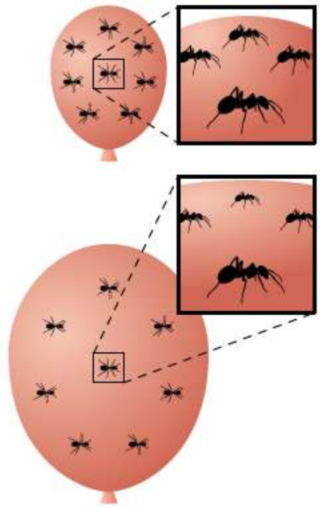


Figure 3 An ant on the surface of an expanding balloon will see all of its ant neighbours moving away from it, just as astronomers on Earth observe galaxies receding away from us.

When we observe the Universe around us, galaxies are receding away in all directions, just as the ants are all moving away from each other. Space itself is expanding. Unlike for the ants, this expansion occurs in three spatial dimensions rather than just two.

Hubble's law

Hubble's law allows us to calculate how fast distant objects, such as stars, are receding from the Earth.

As the Universe expands, light travelling through it is 'stretched' such that its wavelength increases. Light's wavelength being increased is a process known as a redshift, due to how visible light will appear more red when its wavelength is increased. By comparing the detected electromagnetic spectra from distant stars to the spectra we would expect without expansion, we can determine how quickly the Universe is expanding.

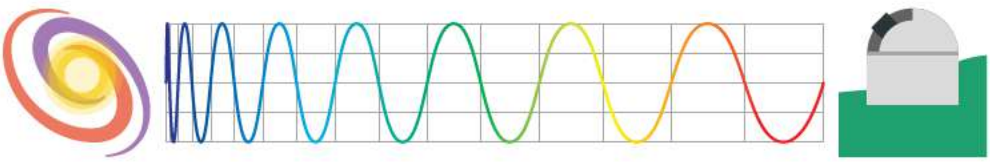


Figure 4 The wavelength of light increases as it travels through expanding space, causing a redshift in distant objects like stars and galaxies.

Scientists have made several key observations that support these theoretical predictions:

- The recessional velocity of an object from a point is roughly proportional to its distance from that point: $v \propto d$.
- Light from distant objects in every direction is redshifted.
- Light from distant objects is redshifted more than light from nearby objects.

As our ability to make accurate measurements has increased, we have better quantified the constant that relates these two variables in Hubble's law.

$$v = H_0 d$$

v = recessional velocity (m s^{-1}), H_0 = Hubble constant (2.27×10^{-18} s^{-1}), d = distance (m)

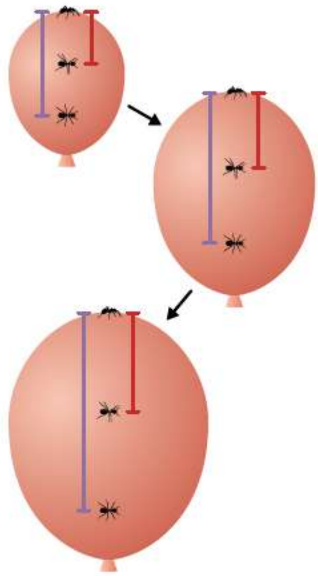


Figure 5 The distance an ant will need to travel to reach its friend will increase faster the further away they are.

Hubble's law is not accurate on small scales dominated by gravity – galaxies relatively close to the Earth (less than 5×10^6 light-years) tend to move towards us rather than travel away. Instead, the law applies to large distances where the recessional velocities of objects are mainly due to the expansion of space rather than their movement through space. Determining Hubble's law relies on observing these distant objects. The discovery of this law provided the first and arguably most important observational evidence for an expanding universe, which is an important prediction of the Big Bang Theory.

Another consequence of the constant expansion of space is that the distance that light needs to travel to reach a certain point constantly increases. As a result, light from certain points in space too far away from us can never reach us, and we can only see what is termed the observable Universe.

Returning to the balloon analogy, consider how the distance between ants affects how fast they are moved apart (Figure 5). Since there is more of the balloon's expanding surface between more distant ants, the space between these ants increases faster. At a large enough separation, two ants will be unable to run towards each other faster than the distance between them is increasing.

The observable Universe is 92 billion light-years (9.2×10^{10} ly) in diameter. A light-year is equal to the distance travelled by light in one year (9.46×10^{15} m), which means the observable Universe has a diameter of $9.2 \times 10^{10} \times 9.46 \times 10^{15} = 8.7 \times 10^{26}$ metres.

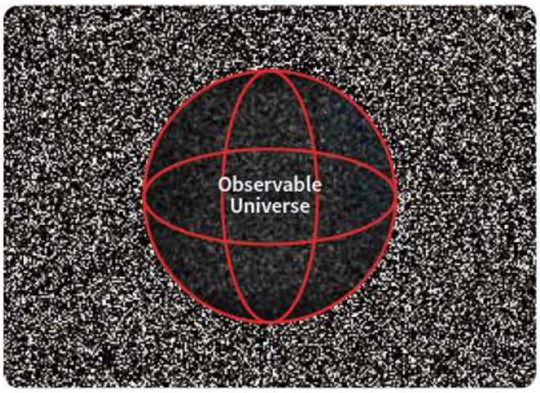


Figure 6 The observable Universe is a region within the Universe. The spherical boundary of the observable Universe is made up of the furthest points in the Universe from which light has had time to travel to Earth (or the observer). This spherical boundary is always growing with time since light can travel further with more time. The size of the Universe is unknown and may be infinite.

Worked example 1

The brightest event ever observed is the gamma-ray burst GRB 080319B, originating from a source 7.5 billion light-years away.

How fast is the source receding from Earth?

Working	Process of thinking
$d = 7.5 \times 10^{6} \times 9.46 \times 10^{15} = 7.1 \times 10^{22}$ m	Convert the distance from light-years to metres.
$v = H_0 d$	Use Hubble's law, with $H_0 = 2.27 \times 10^{-18}$ s^{-1}, to calculate the recessional velocity.
$v = 2.27 \times 10^{-18} \times 7.1 \times 10^{22}$	
$v = 1.6 \times 10^{5}$ m s^{-1}	

The cosmic microwave background

Over the billions of years since the first radiation able to travel long distances was emitted during recombination, the Universe has continued to expand. As a result, some of this ancient light is only reaching us now, as it has needed to travel large distances to finally reach our telescopes. It is as if this light has taken almost 14 billion years to travel the wrong way along a cosmic escalator before finally reaching Earth.

This light is constantly arriving at Earth (and everywhere in the Universe) and is nearly perfectly uniform in all directions – a 'cosmic microwave background' (CMB). This light is a near-perfect black body spectrum in the form of faint microwaves, and it is exactly what would be predicted if it was the (highly redshifted) light from recombination emitted more than 13 billion years ago. As expansion and recombination are key predictions of the Big Bang Theory, the CMB provided key evidence for scientists that the theory was correct.

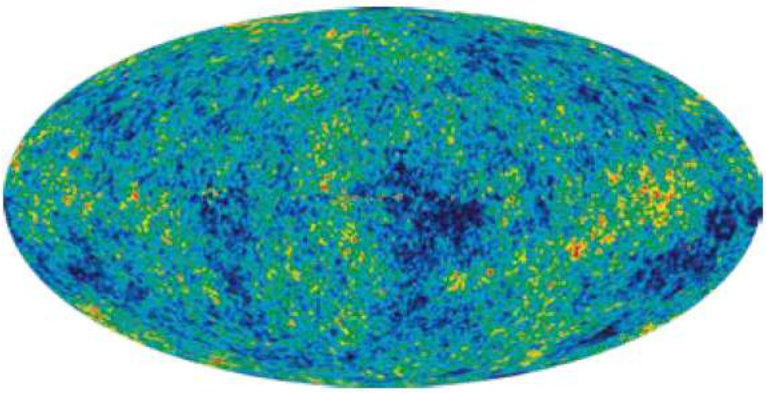


Figure 7 The cosmic microwave background is faint microwave radiation that is nearly uniform in all directions. This electromagnetic radiation originates from the first neutral atoms, formed during recombination.

Relative abundance of elements

The Big Bang Theory predicts that there was a short period of time, roughly ten seconds to twenty minutes after the Big Bang, in which the conditions of the Universe would allow for nuclear fusion reactions to occur. This 'Big Bang nucleosynthesis' would lead to predictable values for the relative abundances of light nuclei in the Universe.

We can observe ancient light from young, undisturbed regions of the Universe to make measurements of the ratios of nuclei as they were in the early Universe. The measured abundances all agree with theoretical calculations and hence provide strong evidence to support the Big Bang Theory.

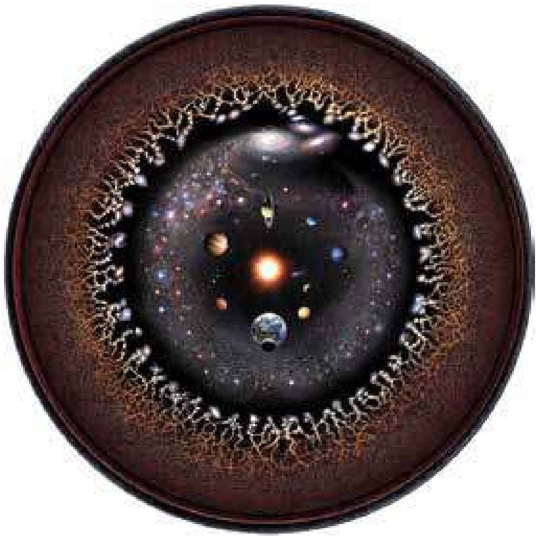


Figure 8 A logarithmic (non-linear) scale depiction of the observable Universe. The centre shows the solar system around us. The further from the centre, the further away from us on Earth and the further back in time we are looking (due to older light reaching us from these points). The outermost reddish line is the Universe at the time of recombination.

Theory summary

- The Big Bang Theory models the Universe from its earliest known period through to its large-scale expansion and evolution.
  - At a finite time in the past, the Universe had an extreme density and temperature.
  - The hot, dense Universe rapidly expanded and cooled.
  - The four fundamental forces separated and matter and antimatter formed asymmetrically.
- As our understanding of the Universe has progressed, we have gained an increasing amount of observational evidence to support the Big Bang Theory.
  - Scientists have observed that space is uniformly expanding.
  - Distant objects are receding from us at a rate proportional to their distance from Earth. This relationship is quantified by Hubble's law.
  - The hot early Universe emitted a large amount of black body radiation during recombination, which is detectable as the cosmic microwave background.
  - The early Universe had a short period of time in which nuclear fusion occurred, known as Big Bang nucleosynthesis. This leads to predictable ratios of light nuclei, which we can observe with light from distant, undisturbed matter.
- The scale of measurements of the Universe is immense and hence requires the use of scientific notation to easily describe both the incredibly small and the incredibly large.

KEEN TO INVESTIGATE?

YouTube video: PBS Digital Studios – What's Wrong With the Big Bang Theory?
youtu.be/JDmKLXVFJzk

Website: Scale of the Universe 2
htwins.net/scale2

ScienceAlert – This Is the Most Exciting Crisis in Cosmology
sciencealert.com/we-can-t-figure-out-how-fast-the-universe-is-expanding-here-s-why

Nova – Absolute Hot
pbs.org/wgbh/nova/zero/hot.html

CONCEPT DISCUSSION QUESTION

We have established that light travels at a finite speed, *c*, and that space is expanding in all directions. This expansion means that the further an object is from us, the faster it is receding.

Scientists hypothesise a potential scenario where the rate of expansion of space increases indefinitely (that is, where Hubble's constant increases over time). If this hypothesis is true, how will the Universe appear differently to what we can see now?

Discuss.

Answers on page 507

Hints

Is there any limit to how fast space can expand?

What happens to our view of objects when their recessional velocity is faster than the speed of light?

What is the effect of increasing Hubble's constant on the number of objects we can observe?

7C Questions

THEORY REVIEW QUESTIONS

Question 1

Fill in the gaps in the following paragraph that describes how helium was formed in the early Universe.

The early Universe was extremely __________ (hot/cold) and __________ (sparse/dense). At first, the __________ (elementary particles/fundamental forces) were unified, and only after they completely separated could __________ (particles/forces) exist. After the Universe cooled some more through expansion, __________ (baryons/isotopes) and then atomic nuclei were able to form. In a period of 20 minutes, __________ (baryogenesis/recombination/Big Bang nucleosynthesis) formed the vast majority of the helium that makes up our Universe today.

Question 2

Match the phenomena in the following list to the epoch of the Universe that is characterised by them. Note that some of the epochs are associated with multiple phenomena.

Phenomena

- Lepton formation and annihilation
- Quark formation and annihilation
- Four fundamental forces unified
- Relatively rapid expansion of space
- Neutral atom formation
- Light of the CMB generated

Epochs

a Planck epoch

b Inflationary epoch

c Quark epoch

d Recombination

Question 3

At a distant time in the future, how would you expect the wavelength of the cosmic microwave background to change?

A The wavelength will be longer than it currently is (redshifted).

B The wavelength will be shorter than it currently is (blueshifted).

C The wavelength will be the same as it currently is.

D The cosmic microwave background will no longer reach Earth.

Question 4

The light from two distant galaxies is observed to be redshifted. The closer of the two galaxies is calculated to be receding at x km s^{-1}. If the second galaxy is four times further away, how fast would it be expected to be receding?

A $\frac{x}{4}$ km s^{-1}

B x km s^{-1}

C $4x$ km s^{-1}

D $16x$ km s^{-1}

Question 5

Hubble's law quantifies the observation that galaxies are moving away from Earth at velocities proportional to their distance. What does this observation imply?

A The space between galaxies is expanding.

B The Earth is at the centre of the Universe.

C Galaxies are still moving away from where the big bang originally was.

D Galaxies exert forces on each other, repelling them apart.

Question 6

The size of the Universe continues to grow larger over time. Which of the following statements **best** models this expansion?

A Everything in the Universe is flying away from the point where the Big Bang occurred.

B Gravitational forces continue to push antimatter further away from the centre of the Universe.

C Objects continue to move away into empty space, and so the Universe gets bigger.

D The space between objects expands uniformly.

Question 7

Which of the following is evidence that supports the Big Bang Theory? *(Select all that apply)*

I The observation that space is expanding

II The presence of a near-uniform cosmic microwave background radiation

III Undisturbed matter from the early Universe having a predictable ratios of nuclei

IV The emergence of life on Earth

Question 8

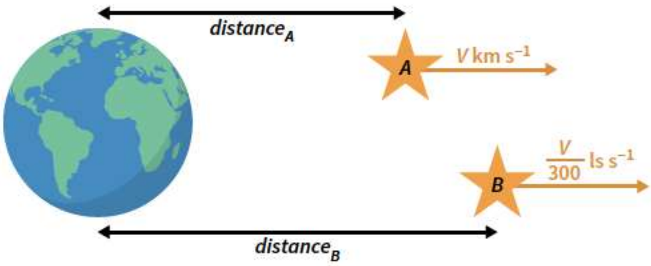
By considering the radius of Earth (6.4×10^3 km) and the radius of the Sun (7.0×10^5 km), approximate how many Earths wide the Sun is.

A 10^1 **B** 10^2 **C** 10^3 **D** 10^4

DECONSTRUCTED EXAM-STYLE QUESTION

Question 9 (4 MARKS)

An astronomer is measuring the recessional velocity of two stars. Star *A* is receding at a rate of V km s^{-1}. Star *B* is receding at a rate of $\frac{V}{300}$ light-seconds per second.



Prompts

a What is the recessional velocity of star *A*, expressed in SI units?

A $V \times 10^{-3}$ m s^{-1}

B V m s^{-1}

C $V \times 10^{3}$ m s^{-1}

D V^2 m s^{-1}

b How does the numerical value of a velocity expressed in light-seconds per second compare to when expressed in metres per second?

A The numerical value is higher in metres per second.

B The numerical value is lower in metres per second.

C The numerical values are equal.

c What is the recessional velocity of star *B*, expressed in SI units?

A $\frac{V}{300} \times 3.0 \times 10^{8}$ m s^{-1}

B $\frac{V}{300} \times 10^{3}$ m s^{-1}

C V m s^{-1}

D $\frac{V}{300} \times \frac{1}{3.0 \times 10^{8}}$ m s^{-1}

d The ratio $\frac{distance_B}{distance_A}$ is given by

A $\frac{v_A}{v_B}$

B $v_A \times v_B$

C $\frac{v_B}{v_A}$

D $H_0 \times \frac{v_B}{v_A}$

Question

e By what factor is star *B* further away from Earth than star *A*? (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 10 (1 MARK)

The Sun is 1.5×10^{11} m from Earth. Acrux, the star system that forms the bottom point of the Southern Cross, is approximately 3×10^{18} m from Earth. How many times further is Acrux from Earth compared to the Sun?

A 2

B 2×10^{7}

C 1.5×10^{18}

D 4.5×10^{29}

Question 11 (3 MARKS)

Identify one of the predictions of the Big Bang Theory. What observational evidence is there to support this prediction?

Question 12 (3 MARKS)

Arno and Robert are discussing the cosmic microwave background. Arno argues that it can only be detected by pointing a radio telescope towards the centre of the Universe. Robert disagrees and suggests it is nearly uniform in all directions. Who is correct? Justify your response.

Question 13 (4 MARKS)

a The Andromeda galaxy is the nearest major galaxy to our own, only 2.4×10^{19} km away. How fast would you expect it to be receding, based on Hubble's law? (2 MARKS)

b The Andromeda galaxy has been found to not be receding from us, and will in fact collide with the Milky Way Galaxy in 4 billion years. Explain the discrepancy between this observation and your answer for part **a**. (2 MARKS)

Question 14 (3 MARKS)

Nearly all of the objects in the Universe we observe are made of matter, with very little antimatter, yet matter and antimatter form in pairs that annihilate on impact. Explain why there is so much more matter.

Question 15 (2 MARKS)

Measuring the expansion of the Universe involves observing on enormous scales, far beyond the Solar System and even the Milky Way Galaxy. Explain why it would be inaccurate to measure nearby objects as a way of quantifying the expansion of the Universe.

Question 16 (3 MARKS)

The name 'Big Bang' invokes the notion that the Universe is exploding outwards from a single point. Is this model consistent with observational evidence? Explain your answer.

Previous lessons

Question 17 (2 MARKS)

A particular light bulb is designed to draw 8.3 A when supplied by an ideal 12 V power supply. What resistance should be chosen for the light bulb?

Question 18 (3 MARKS)

Ernest and William are conducting an experiment to examine the effects of gamma radiation. William suggests that they should use an aluminium casing to protect the equipment from alpha and beta radiation, but Ernest argues that nothing more than a sheet of paper is necessary. Who is correct? Discuss your response.

Key science skills

Question 19 (7 MARKS)

A group of students obtained a set of data points from a local observatory to investigate Hubble's law.

Galaxy	Recessional velocity ($\times 10^6$ m s^{-1})	Distance from Earth ($\times 10^6$ ly)
Triangulum	−0.179	2.73
The Black Eye	0.408	17.3
The Sombrero	1.02	31.1
The Little Sombrero	1.05	40.0
Medusa Merger	2.50	129
The Mice Galaxies	6.61	290

a Use the data set to plot recessional velocity against distance from Earth. Be sure to include axis labels, appropriate units, and a line of best fit. (4 MARKS)

b What is the gradient of the line of best fit? Give your answer in SI units. (2 MARKS)

c What does this gradient represent? (1 MARK)

CHAPTER 7 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

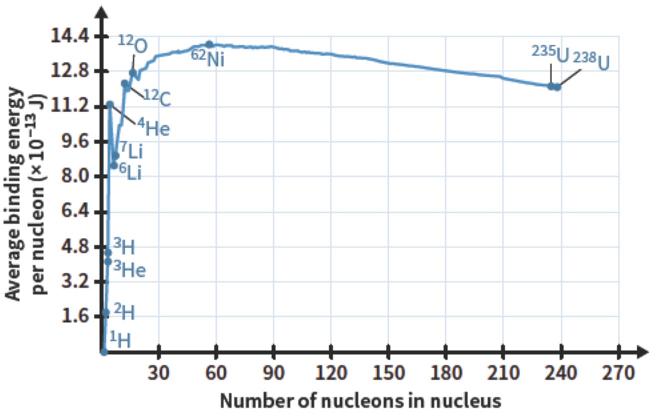
SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

The provided diagram shows the binding energy values against mass number.



Which one of the following statements regarding nuclear fusion and fission is **incorrect**?

A Nuclear fusion generally occurs between multiple light nuclei and nuclear fission generally occurs for a single heavy nucleus.

B The fission of 1 gram of uranium-235 will release more energy than the fusion of 1 gram of protons (^{1}H).

C The difference in binding energies per nucleon for fusion reactions is generally greater than the difference in binding energies per nucleon for fission reactions.

D In both fusion and fission reactions, the mass of the products is less than the mass of the reactants.

Question 2

Which one of the following statements about electromagnetic waves is correct?

A Electromagnetic waves travel at different speeds in a vacuum depending on their frequency.

B Electromagnetic waves maintain a constant wavelength as they travel through expanding space.

C Electromagnetic waves are perpendicular oscillating electric and magnetic fields.

D Electromagnetic waves require a medium like air to travel through.

Question 3

Which one of the following statements about light from a synchrotron is **false**?

A Light is emitted tangentially to the charged particles' path.

B Photons are accelerated within the storage ring to near the speed of light.

C Synchrotron light is emitted at a broad range of electromagnetic frequencies.

D Synchrotrons can contain linear accelerators.

Question 4

Which one of the following is considered evidence in support of a universe that expanded from a hot, dense initial state?

A Cosmic microwave background radiation

B The redshifting of electromagnetic spectra emitted by faraway galaxies

C The near-uniform density of matter distributed across the observable Universe

D All of the above

Question 5

Which one of the following statements about the early Universe is incorrect?

A During the inflationary epoch, space was expanding extremely rapidly.

B Antimatter and matter formed through pair production processes during the quark epoch.

C In the hadron epoch, antimatter and matter particles annihilated, leaving behind an equal amount of matter and antimatter.

D During Big Bang nucleosynthesis, atomic nuclei began to form from protons and neutrons.

SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

The following nuclear reaction releases 8.7 MeV of energy. What is the difference in total mass between the products and the reactants? Note that 1 eV = 1.6×10^{-19} J.

$${}^{1}_{1}\text{H} + {}^{11}_{5}\text{B} \rightarrow 3{}^{4}_{2}\text{He} + \textit{energy}$$

Question 7 (4 MARKS)

In 1965, astronomers Arno Penzias and Robert Wilson detected faint microwave radiation that was uniform in every direction. What did they observe and what evidence does this observation provide for the Big Bang theory?

Question 8 (3 MARKS)

The following reaction is used to generate tritium (${}^{3}_{1}\text{H}$).

$${}^{1}_{0}\text{n} + {}^{6}_{3}\text{Li} \rightarrow {}^{3}_{1}\text{H} + {}^{4}_{2}\text{He} + \textit{energy}$$

Use the provided data to calculate how much energy is released in the reaction.

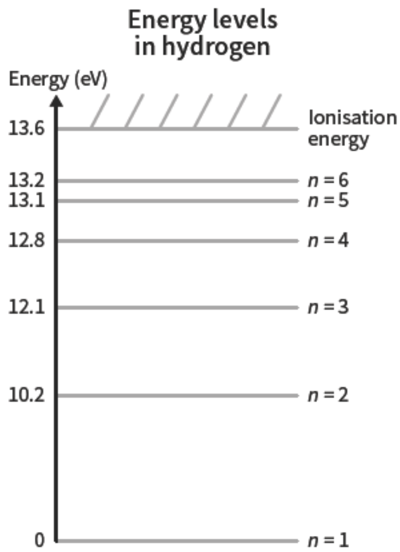
Mass of neutron	$1.6749275 \times 10^{-27}$ kg
Mass of ${}^{3}_{1}\text{H}$	$5.0082709 \times 10^{-27}$ kg
Mass of ${}^{4}_{2}\text{He}$	$6.6464815 \times 10^{-27}$ kg
Mass of ${}^{6}_{3}\text{Li}$	$9.9883519 \times 10^{-27}$ kg

Question 9 (4 MARKS)

An electron in a hydrogen atom absorbs a photon and consequently changes energy state from $n = 2$ to $n = 4$. The energy levels for a hydrogen atom are shown in the diagram provided.

a What is the energy of the incident photon in eV? (1 MARK)

b Determine all the energies of the photons that could be emitted as the electron falls back to the ground state. (3 MARKS)



Question 10 (3 MARKS)

Ben thinks that a synchrotron is able to produce light because the magnets in the synchrotron are able to excite electrons to higher energy levels. When the electrons return to a lower energy level, they emit electromagnetic radiation. Is Ben's explanation for how a synchrotron produces light correct? Justify your answer.

Question 11 (3 MARKS)

Cygnus A was the first radio galaxy ever observed, located 7.57×10^8 light-years from Earth. 1 light-year is equivalent to 9.46×10^{15} m. How fast is Cygnus A receding according to Hubble's Law? Is it likely that Cygnus A is actually receding based on its distance from Earth?

Question 12 (3 MARKS)

The nucleus of the nitrogen-14 isotope contains 7 protons and 7 neutrons. Use the provided data to

a calculate the mass defect in forming one nitrogen-14 nucleus. (2 MARKS)

b calculate how much energy is released in forming one nitrogen-14 nucleus. (1 MARK)

Mass of nitrogen-14 nucleus	2.3252×10^{-26} kg
Mass of proton	1.6726×10^{-27} kg
Mass of neutron	1.6749×10^{-27} kg

Question 13 (3 MARKS)

According to models of cosmological evolution based on the Big Bang theory, the 'dark ages' after recombination lasted for hundreds of millions of years. Explain how the conditions of the early Universe resulted in such a long period in which little light was produced.

UNIT 1, AOS 3 REVIEW

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Which of the following best gives the different types of radiation in order from greatest ionising ability to least ionising ability?

A Alpha radiation, beta radiation, gamma radiation

B Gamma radiation, beta radiation, alpha radiation

C Beta radiation, alpha radiation, gamma radiation

D Alpha radiation, gamma radiation, beta radiation

Question 2

Each particle has a corresponding antiparticle. For a given particle, its antiparticle will have

A a different mass.

B the same mass but the opposite value for all other quantum values (charge, spin, etc.).

C a different mass and the opposite value for all other quantum values (charge, spin, etc.).

D the same mass and spin but the opposite value for all other quantum values (charge, baryon number, etc.).

Question 3

In which one of the following scenarios would light (electromagnetic radiation) be produced by the specified particles?

A Electrons travelling down a straight track at a constant speed

B A neutron accelerating away from an atom after a fission reaction

C Protons travelling around a circular track at a constant speed

D All of the above

Question 4

Consider one variant of the Sigma particle Σ (uds). Considering the provided table, which one of the following statements is correct?

	Charge (e)	Strangeness	Baryon number	Spin
Up quark	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\frac{1}{2}$
Down quark	$-\frac{1}{3}$	0	$+\frac{1}{3}$	$\frac{1}{2}$
Strange quark	$-\frac{1}{3}$	−1	$+\frac{1}{3}$	$\frac{1}{2}$

A The charge of the Sigma particle is +1.

B The baryon number of the Sigma particle is $+\frac{1}{3}$.

C The Sigma particle must be classified as a lepton or a meson.

D The strangeness of the Sigma particle is −1.

Question 5

The provided diagram shows the relative abundance of each of the stable isotopes of ruthenium (atomic number 44).

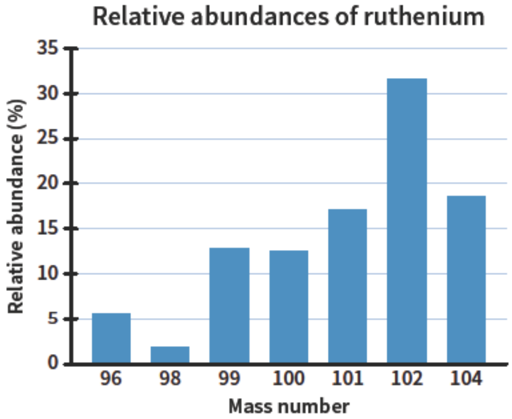
For a randomly selected stable ruthenium atom, the probability of it containing **more** than 57 neutrons is closest to

A 18%.

B 50%.

C 67%.

D 100%. All stable isotopes of ruthenium have more than 57 neutrons.



SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (3 MARKS)

Through repeated α and β^- decays **only**, an actinium-227 nucleus (atomic number 89) decays to a lead-207 nucleus (atomic number 82). Calculate the number of α particles and the number of β^- particles emitted in this decay chain.

Question 7 (9 MARKS)

Axel is investigating the radioactive substances erbium-160 and phosphorus-32. Axel was able to find out that the half-life of erbium-160 is 1.19 days, and he is running some tests to determine the half-life of phosphorus-32.

a The activity of a particular sample of erbium-160, as measured with a Geiger counter, was initially 1.28×10^4 Bq.

Calculate how long Axel would have to wait until the activity dropped below 1.0×10^2 Bq. Give your answer in days. (3 MARKS)

The sample of phosphorus-32 initially weighs 60.0 milligrams, and after 23.0 days only 15.0 milligrams remain.

b Calculate the half-life of phosphorus-32. Give your answer in hours. (3 MARKS)

c Determine the amount of energy released in J (including energy in the form of decay particles) over the 23 days by the decay of the phosphorus-32 sample. (1 MARK)

d After his experiments with the radioactive substances, Axel feels confident enough to put his findings into a report. In one part of his report, Axel states that the basic principle behind the concept of a half-life is that "if you have two radioactive nuclides, after one half-life one of them will decay. As such, half of a radioactive substance will decay after one half-life."

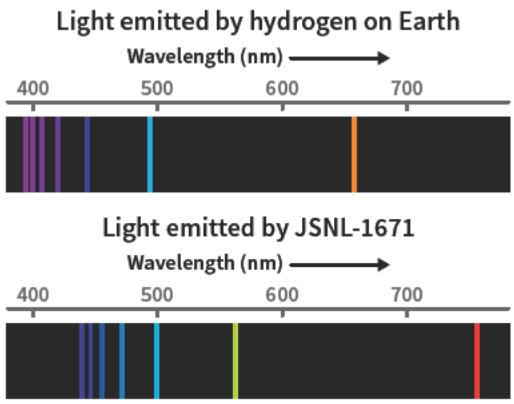
Explain why Axel's statement is incorrect. (2 MARKS)

Question 8 (5 MARKS)

Astronomers have observed a new far-away galaxy named JSNL-1671. They know that the galaxy is composed mostly of hydrogen at a particular temperature. The provided diagrams show the wavelengths of light emitted by hydrogen on Earth at this temperature compared with the wavelengths of light emitted by the galaxy.

The shortest wavelength that the astronomers observe from JSNL-1671 is greater than 400 nm.

a Explain why there is such a significant discrepancy between the two diagrams. (2 MARKS)



b A star at the centre of the galaxy has undergone a supernova explosion. The galaxy is receding from Earth at 4.0×10^{7} m s^{-1}.

Approximate how long it will take for the astronomers on Earth to be able to observe this event using Hubble's Law. Assume that the star is receding at the same rate as the galaxy and ignore the effects of future expansion. Give your answer in years. (3 MARKS)

Question 9 (12 MARKS)

Consider the element uranium-235 ($^{235}_{92}U$). One nucleus of uranium-235 has a mass of 3.902×10^{-25} kg. Take the average mass of a uranium-235 nucleon to be 1.674×10^{-27} kg.

a Explain why the mass of uranium-235's nucleus is less than the mass of its constituent nucleons when they are unbound. (3 MARKS)

b Show that the binding energy for a uranium-235 nucleon is 12.2×10^{-13} J. (2 MARKS)

A uranium-235 atom can undergo nuclear fission to produce xenon-142, strontium-90, and *y* neutrons; as described by the following equation:

$$^{235}U + ^{1}_{0}n \rightarrow ^{142}Xe + ^{90}Sr + y \times ^{1}_{0}n + energy$$

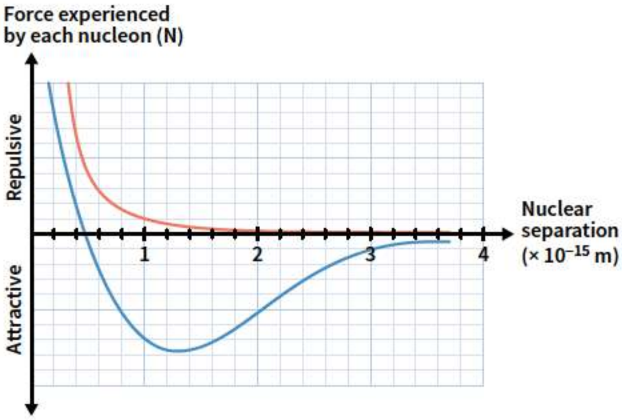
c Use the fission equation to determine the value of *y*. (2 MARKS)

d The binding energy of xenon-142 is 13.3×10^{-13} J per nucleon and the binding energy of strontium-90 is 13.9×10^{-13} J per nucleon.

Calculate the net increase in the number of free neutrons through the fission of uranium-235 atoms if 3.5 MJ of energy is released and it is a chain reaction. (5 MARKS)

Question 10 (4 MARKS)

The provided diagram shows how the strength of the strong nuclear force and electrostatic force acting between two nucleons changes with their separation. The forces are repulsive above the horizontal axis and attractive below it.



Explain how the shape of both graphs relates to the stability of the nucleons in the atomic nucleus. In your answer, refer to which parts of the graph would correspond to stable and unstable nuclei.

Question 11 (3 MARKS)

Explain the similarities and differences between the compositions of baryons and mesons. Which type of particle is more stable?

Question 12 (3 MARKS)

Explain why scientists can use the relative abundances of elements in the Universe to help determine whether the Big Bang Theory is correct.

Question 13 (6 MARKS)

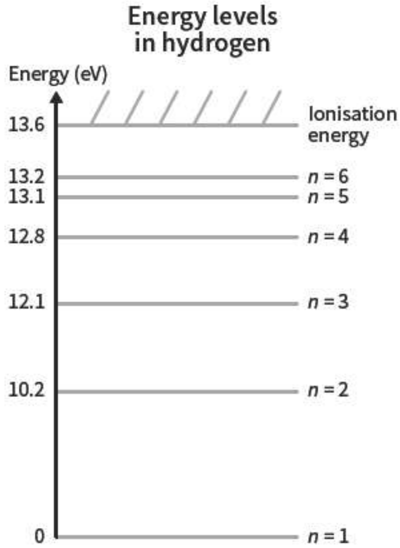
The provided diagram shows the electron energy levels of a hydrogen atom:

a Explain why hydrogen can absorb light with an energy of 12.1 eV but cannot emit light with an energy of 10.0 eV. (3 MARKS)

b An electron in a hydrogen atom is excited to the $n = 5$ state.

List the possible energies of the light that could be emitted as the atom goes from the $n = 5$ state to the $n = 2$ state. (3 MARKS)

Adapted from 2019 VCAA Exam Section B Q18



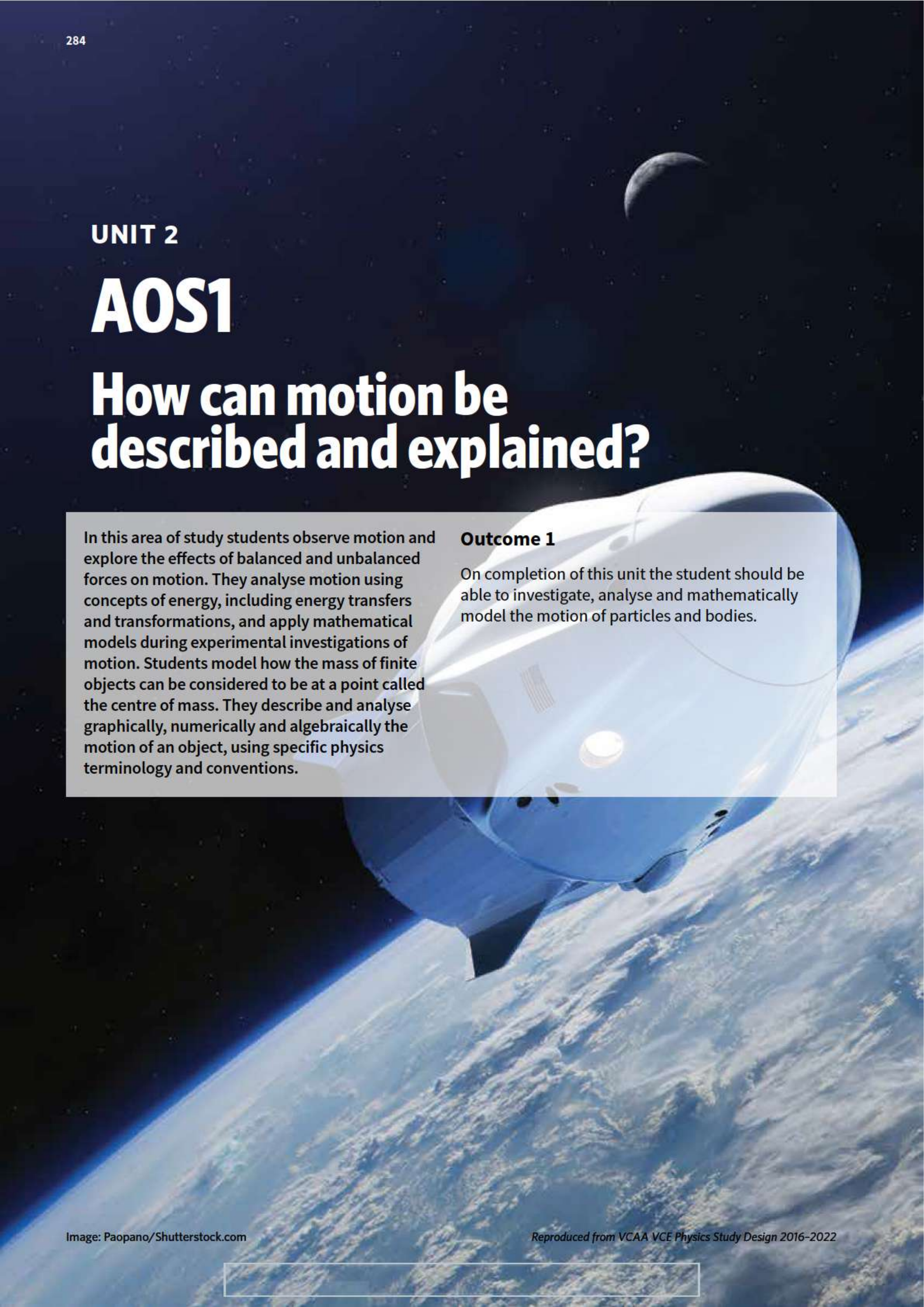
UNIT 2 What do experiments reveal about the physical world?

In this unit students explore the power of experiments in developing models and theories. They investigate a variety of phenomena by making their own observations and generating questions, which in turn lead to experiments. Students make direct observations of physics phenomena and examine the ways in which phenomena that may not be directly observable can be explored through indirect observations.

In the core component of this unit students investigate the ways in which forces are involved both in moving objects and in keeping objects stationary. Students choose one of twelve options related to astrobiology, astrophysics, bioelectricity, biomechanics, electronics, flight, medical physics, nuclear energy, nuclear physics, optics, sound and sports science. The option enables students to pursue an area of interest by investigating a selected question.

Students design and undertake investigations involving at least one independent, continuous variable. A student designed practical investigation relates to content drawn from Area of Study 1 and/or Area of Study 2 and is undertaken in Area of Study 3.

Reproduced from VCAA VCE Physics Study Design 2016–2022



UNIT 2

AOS1

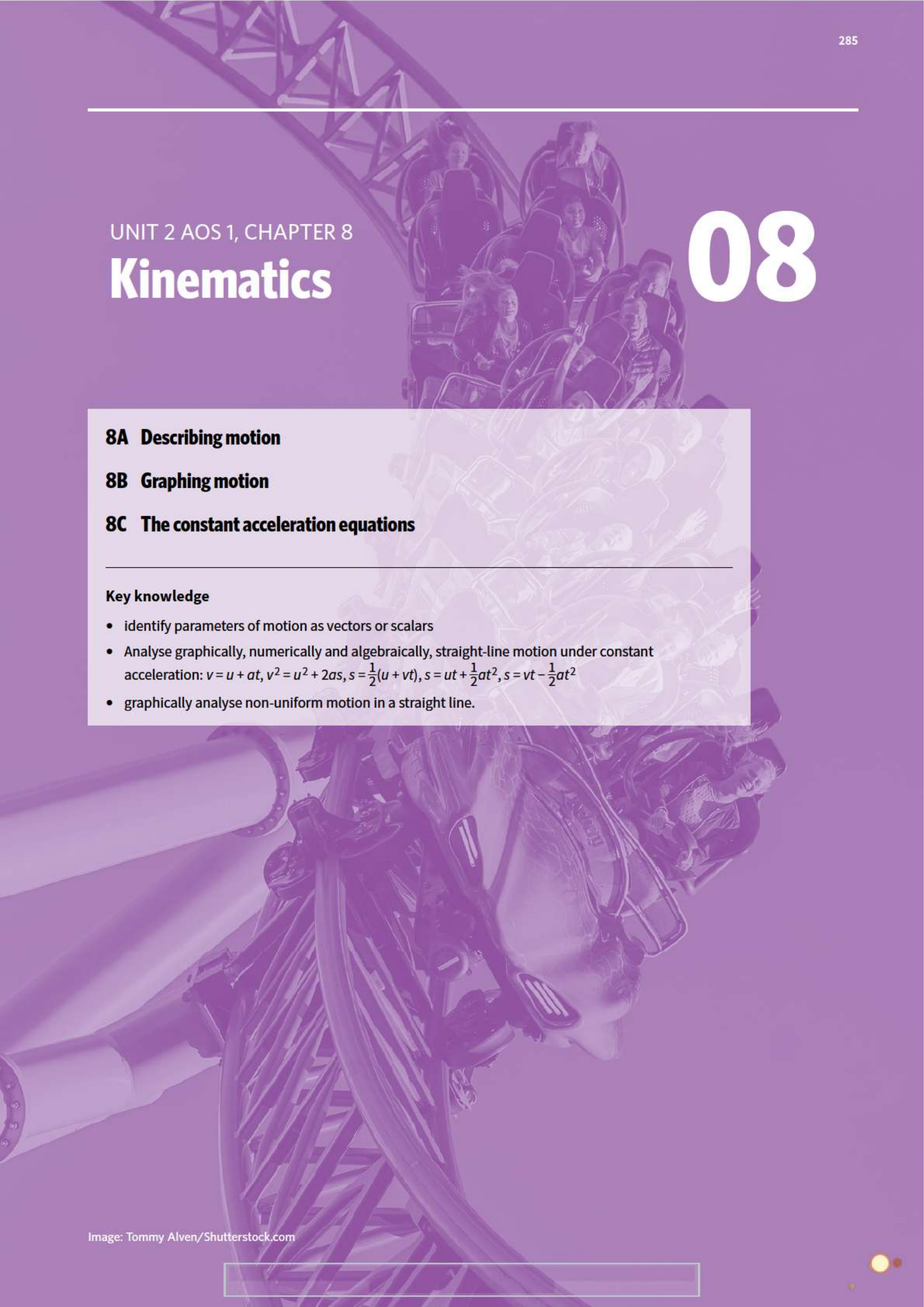
How can motion be described and explained?

In this area of study students observe motion and explore the effects of balanced and unbalanced forces on motion. They analyse motion using concepts of energy, including energy transfers and transformations, and apply mathematical models during experimental investigations of motion. Students model how the mass of finite objects can be considered to be at a point called the centre of mass. They describe and analyse graphically, numerically and algebraically the motion of an object, using specific physics terminology and conventions.

Outcome 1

On completion of this unit the student should be able to investigate, analyse and mathematically model the motion of particles and bodies.

Image: Paopano/Shutterstock.com



UNIT 2 AOS 1, CHAPTER 8

Kinematics

08

Key knowledge

- identify parameters of motion as vectors or scalars
- Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration: $v = u + at$, $v^2 = u^2 + 2as$, $s = \frac{1}{2}(u + vt)$, $s = ut + \frac{1}{2}at^2$, $s = vt - \frac{1}{2}at^2$
- graphically analyse non-uniform motion in a straight line.

Image: Tommy Alven/Shutterstock.com

8A DESCRIBING MOTION

Motion examines how objects navigate and interact with space around them. Unlike other topics in physics, this is something that we all have direct experience with in everyday life. Surprisingly, this does not change the fact that motion can sometimes be more counterintuitive than it might appear.

Whilst we have an existing vocabulary for motion – speed, distance, time, etc. – this lesson will establish a formal language for describing movement of all kinds. We will look at the foundations of scalar and vector quantities and begin to explore key terms like displacement (s), velocity (v) and acceleration (a).

8A Describing motion	8B Graphing motion	8C The constant acceleration equations

Study design dot points

- identify parameters of motion as vectors or scalars
- analyse graphically, numerically and algebraically, straight-line motion under constant acceleration: $v = u + at$, $v^2 = u^2 + 2as$, $s = \frac{1}{2}(u + v)t$, $s = ut + \frac{1}{2}at^2$, $s = vt - \frac{1}{2}at^2$

Key knowledge units

Scalars and vectors	2.1.1.1
Constant velocity motion	2.1.2.1
Acceleration	2.1.2.2

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$speed = \frac{distance}{time}$ average speed
	$v_{avg} = \frac{\Delta s}{\Delta t}$ average velocity
	$a_{avg} = \frac{\Delta v}{\Delta t}$ average acceleration

Definitions for this lesson

acceleration the rate of change of velocity per unit time (vector quantity)

displacement the change in position of an object, or the shortest path (including direction) between the initial and final positions (vector quantity)

distance the total length of a given path between two points (scalar quantity)

scalar quantity a quantity that has only magnitude (size)

speed the rate of change of distance per unit time (scalar quantity)

vector quantity a quantity that has both magnitude (size) and direction

velocity the rate of change of displacement per unit time (vector quantity)

Scalars and vectors 2.1.1.1

OVERVIEW

Scalars are measurements that have only magnitude, whereas vectors have both magnitude and direction. Distance is a scalar that measures the total length of the journey covered moving between two points. Displacement is a vector that is a measurement of the change in position of an object.

THEORY DETAILS

At this point in time, we are familiar with what a scalar is, even if the term is a new one. This is a type of measurement that associates a magnitude to something. It gives us a description of a quantity's size, but nothing else. Examples include mass, length, time and even can extend to things outside of physics like money.

What are vectors?

Vectors are quantities that have both a magnitude (size) and a direction. In physics, we generally represent them as arrows in space.

- The length of the arrow represents the quantity's magnitude.
- The direction in which the arrow is pointing represents the relative direction of the measurement.

Though the name itself might be new to you, the concept itself is something that appears in everyday life, just like scalars.

Suppose, for instance, you were telling someone the location of a building from where you were currently standing. It would not help much to simply tell them the distance they have to walk to get there ("The tuckshop is 100 metres away"). You would need to add a direction ("The tuckshop is 100 metres **to the left**").

There are some points worth making with regard to how the direction is communicated:

- This direction can be communicated in many ways: cardinal directions (e.g. North), words like left and right, and angles given relative to a particular direction.
- When using vectors in one dimension, we will mostly use positive (+) and negative (−) signs to distinguish direction. The direction defined as positive can be changed for convenience depending on the situation.

We have explored how scalar quantities can be combined to give a net measurement and this is also the case for vectors. However, it is not a simple matter of just adding the magnitudes and directions together. When operating with vectors, we have to represent the operation geometrically to ensure we find the correct magnitude and direction. Because of this, we can see that the direction of the arrow, and not just its magnitude, is important.

We can think of 1D vectors as being arrows on a number line. Whenever the vector arrows are pointing in the same direction, we can add them by putting the end of one arrow at the start of the other, as shown in Figure 1, otherwise known as the 'tip-to-tail' method.

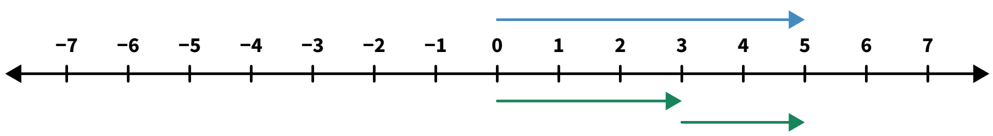


Figure 1 We can imagine 1D vector quantities as moving along a one-dimensional number line. The two green vectors both represent movements in the positive direction. The blue arrow represents the net effect of adding the two arrows together tip-to-tail.

We can also combine 1D vectors when they do not point in the same direction. For vectors that represent movement in the negative direction, we account for this by flipping the arrow as shown below in Figure 2. Here, the green arrows show a displacement of 3 metres to the right followed by a displacement of 7 metres to the left. To evaluate the sum of the vectors we can then still use the tip-to-tail method.

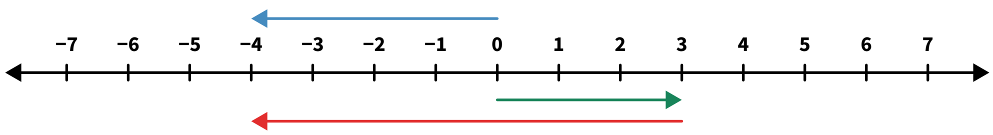


Figure 2 We now have one of the vectors pointing in the positive direction and one in the negative. We can still combine these two vectors together, with the net effect of this combination shown by the blue arrow.

We can also represent and combine 2D vectors. We can think of 2D vectors as being arrows in a Cartesian plane. As shown in Figure 3, a vector can be communicated either with:

- the components in the two perpendicular directions (*x* and *y*-directions) or
- a magnitude and an angle measured relative to a reference direction (such as the positive direction of the *x*-axis).

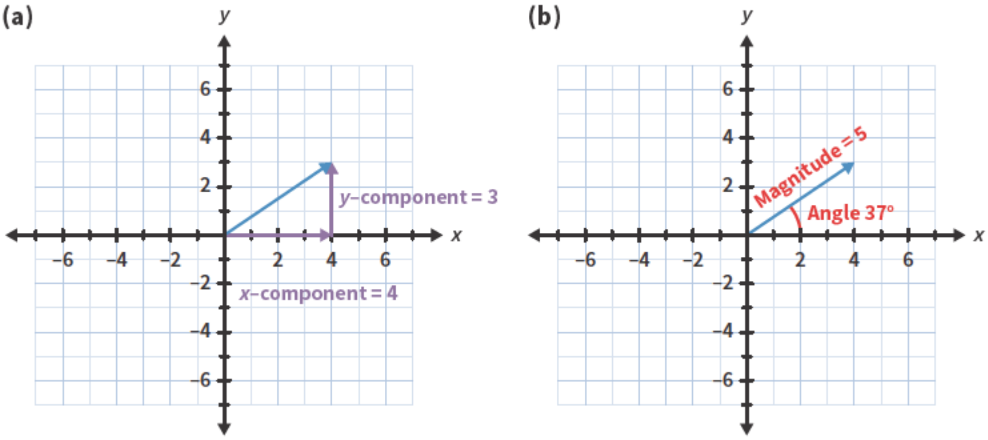


Figure 3 A vector can be represented by either **(a)** an *x*-component and a *y*-component or **(b)** a magnitude and an angle (which is measured from the positive direction of the *x*-axis in this case).

Figure 4(a) shows two vectors, v_1 and v_2. We can again use the tip-to-tail method to add these two vectors. The result is shown by the orange vector in Figure 4(b).

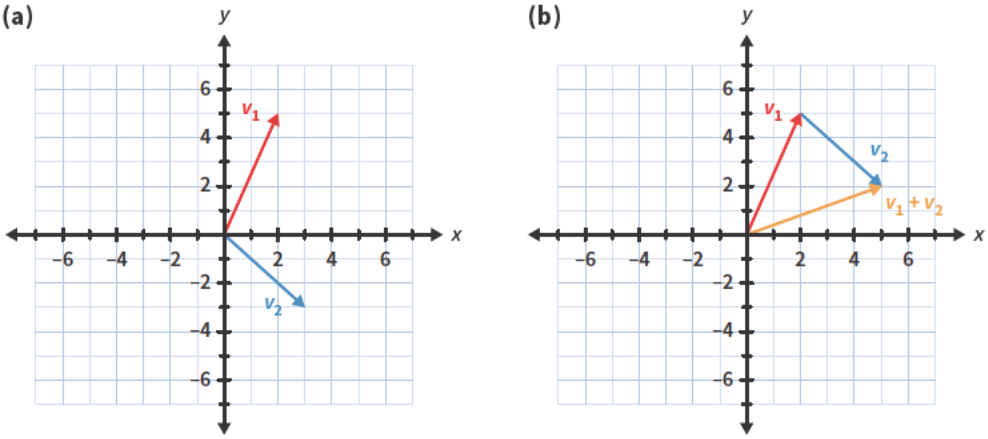


Figure 4 **(a)** Two vectors, v_1 and v_2 **(b)** can be added using the tip-to-tail method, which produces the orange vector.

Table 1 A summary of scalars and vectors, and how to perform operations with each type of quantity.

Type of quantity	How to represent it	How to use in operations
Scalars	Measurements of a certain size that we can linearly combine through addition, subtraction, multiplication or division	Substitute the magnitude into the operation
Vectors	1D Vectors – Arrows that represent physical quantities applied in one dimension. Direction is commonly represented by positive and negative values. 2D Vectors – Arrows that represent physical quantities applied in two dimensions (such as up/down and left/right). Direction is commonly represented by an angle.	Draw the vectors using the tip-to-tail method. For subtraction, flip the subtracted vector. Find the length and direction of the resultant arrow.

Displacement and distance

Distance, *d*, describes the total length of a path that an object travels.

- The SI unit for distance is metres (m).
- It is a scalar quantity, so it only describes the magnitude of the path.

Displacement, *s*, describes the change in position of an object from one point in time to another.

It is important to understand that the magnitude of displacement is not always equal to distance. Since distance is a scalar quantity, it does not account for changes in direction. So, whenever there is a change in direction, the magnitude of displacement will not be equal to the distance travelled.

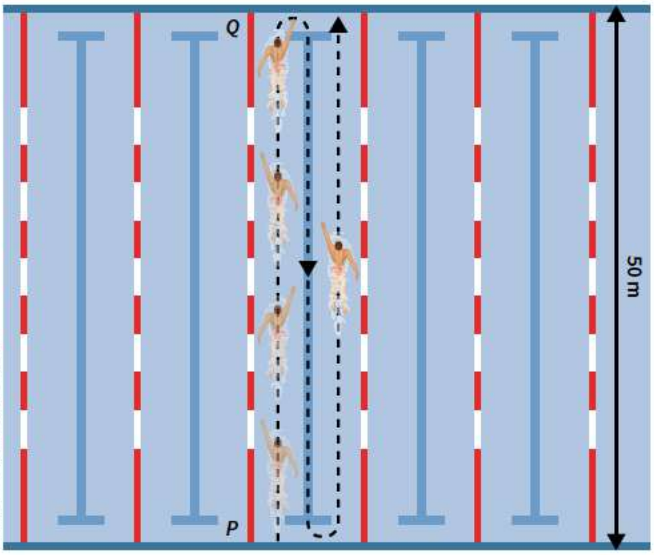


Image: MSSA/Shutterstock.com

Figure 5 A swimmer swimming lengths of a 50-metre swimming pool

To highlight this difference, consider Figure 5 which shows someone swimming three laps of a 50-metre pool, starting from the end labelled *P*.

- The distance travelled is 50 + 50 + 50 = 150 m.
- The magnitude of the displacement, however, is 50 m since the finish (point *Q*) is 50 m from the start (point *P*).

Displacement in two dimensions

In our swimming analogy, we were only considering motion in one direction. However, in VCE Physics, it is often important to be able to think in two dimensions. A useful analogy might be to compare displacement to playing a hole of golf.

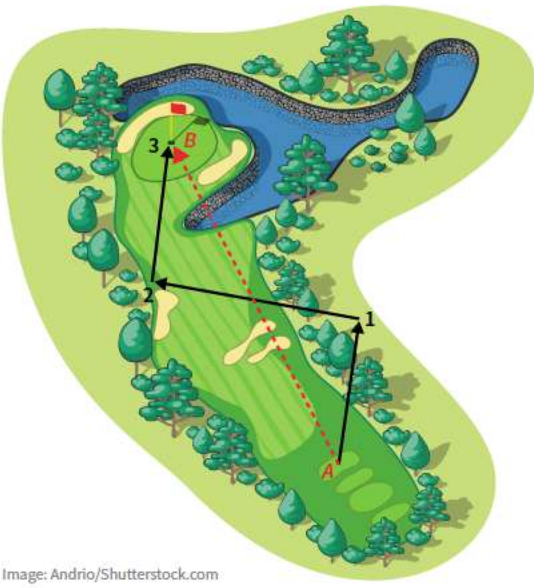


Image: Andrio/Shutterstock.com

Figure 6 A simple depiction of how a golf hole was played. Here, the three shots take a much longer route than the direct line (red) from the tee to the hole.

Any golf hole can be broken down into a series of shots. In Figure 6, the black arrows represent each individual shot, showing how the ball takes a very indirect path to get to the location of the hole located at the end of the arrow labelled 3.

Regardless of how we moved from point *A* (the tee) to point *B* (the hole), when it comes to displacement all that matters is that we moved from *A* to *B*. Where distance travelled considers the unique path the object took, displacement accounts only for the net outcome of the movement.

USEFUL TIP

Since displacement is a vector and distance travelled is a scalar, the magnitude of displacement will always be less than or equal to the distance travelled. Use this fact to check whether your answers make physical sense when doing calculations.

Constant velocity motion 2.1.2.1

OVERVIEW

Speed is a scalar that measures how the distance travelled changes per unit time. Velocity is a vector that measures how the displacement changes per unit time. Both can be used to describe how fast something is moving, although depending on the motion they produce different descriptions.

THEORY DETAILS

In our vocabulary of describing motion, it will be important to define a term for how fast something is moving. The concept you are likely familiar with is **speed**, which is the rate of change of distance travelled per unit time.

- The SI unit for speed is metres per second ($m\,s^{-1}$).
- Speed is a scalar quantity.

To calculate the average speed of an object, we divide the distance travelled by the time taken.

$$speed = \frac{distance}{time}$$

Velocity is the rate of change of displacement per unit time.

- The SI unit for velocity is metres per second ($m\,s^{-1}$).
- Velocity is a vector quantity.

Suppose we are driving in a golf buggy and we drop a golf ball out the back of the buggy every second, as shown in Figure 7. In both Figure 7(a) and Figure 7(b) the balls land and stop five metres apart in a straight line.

- The magnitudes of both the speed and velocity in Figure 7(a) are $5\ m\,s^{-1}$ since there is no change in direction.
- By contrast, in Figure 7(b) the buggy follows a curved path. The magnitude of the **average velocity** is $5\ m\,s^{-1}$, however the **average speed** must be greater than $5\ m\,s^{-1}$ due to the greater distance travelled by the buggy along its curved path.

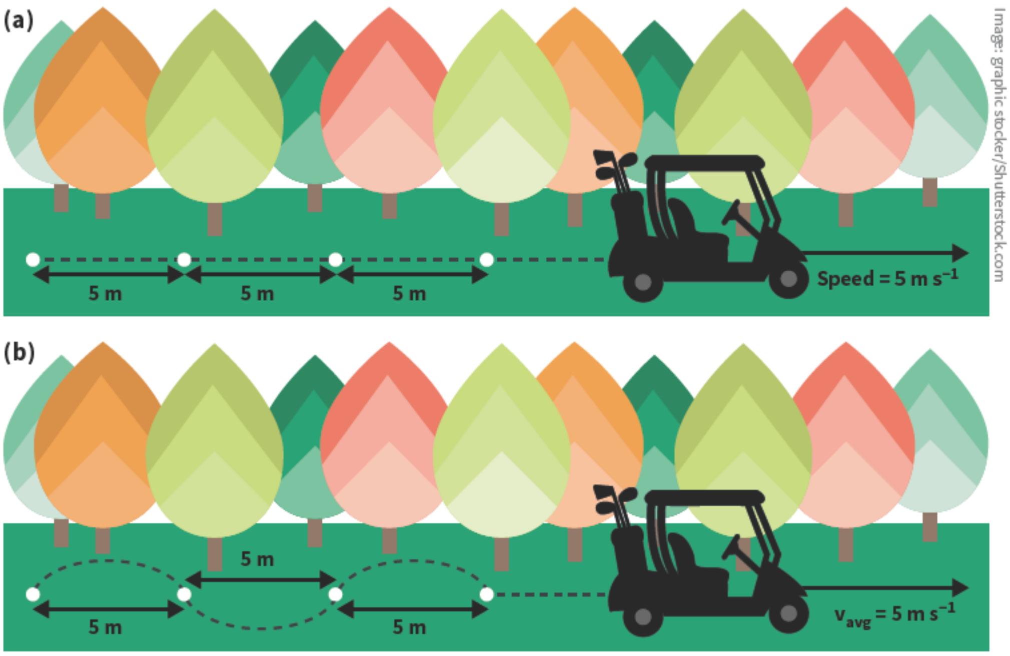


Figure 7 **(a)** A golf buggy travelling such that its speed and magnitude of velocity are both $5\ m\,s^{-1}$. **(b)** A golf buggy travelling with a varying velocity but also an average velocity that has a magnitude of $5\ m\,s^{-1}$.

This allows us to make three observations:

- Velocity is a measure of how much an object is displaced (or displaces itself) per unit time – in this case we have used one second units.
- A higher velocity corresponds to a greater displacement between consecutive golf balls when compared to a lower velocity.
- The displacement (spacing) between consecutive golf balls will be the same if the golf buggy is travelling at constant velocity.

The average velocity of an object can be calculated with the following formula. Note that s_1 and s_2 represent the displacement of the object at time t_1 and t_2 respectively.

$$v_{avg} = \frac{\Delta s}{\Delta t} = \frac{s_2 - s_1}{t_2 - t_1}$$

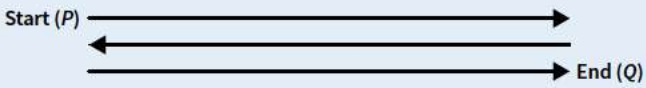
v_{avg} = average velocity (m s^{-1}), Δs = change in displacement (m), Δt = change in time (s)

Worked example 1

Sam swims three laps of a 25 m pool in 120 s starting from one end *P* and swimming towards the other end *Q*.

a Calculate Sam's average speed.

b Calculate Sam's average velocity.

Working	Process of thinking
a $distance = 3 \times 25 = 75$ m	Calculate distance travelled.
$speed_{avg} = \frac{distance}{\Delta t} = \frac{75}{120} = 0.625 = 0.63$ m s^{-1}	Use this result to find Sam's average speed.
b $\Delta s = s_2 - s_1 = 25 - 0 = 25$ m	Sam's change in displacement is 25 metres since this is the distance between his initial and final position.
	
$v_{avg} = \frac{\Delta s}{\Delta t} = \frac{25}{120} = 0.21$ m s^{-1}	Substitute in values for time and displacement to calculate Sam's velocity.

Acceleration 2.1.2.2

OVERVIEW

Acceleration is a vector, that measures how the velocity changes per unit time. It describes changes in direction of a moving object, as well as whether the object is speeding up or slowing down.

THEORY DETAILS

We define acceleration to be the rate of change of velocity per unit time.

- The SI unit for acceleration is metres per second per second (m s^{-2}).
- Acceleration is a vector, like displacement and velocity, so it requires a direction as well as a magnitude.
- In everyday language, we generally associate acceleration with 'speeding up'. However, since velocity is a vector, acceleration can occur without the speed changing.
  - Acceleration occurs when the magnitude of velocity increases or decreases (i.e. the object speeds up or slows down).
  - Acceleration also occurs when the direction of velocity changes (even if the speed is constant).
  - The term deceleration can be used when the object slows down (speed decreases).

In Figure 7(a), the golf buggy travelled in a straight line with constant displacement (indicated by the golf balls) for each unit of time. This represented constant velocity. If velocity is visualised by the displacement between balls for each unit of time, then acceleration can be visualised by how this displacement changes from one unit of time to the next.

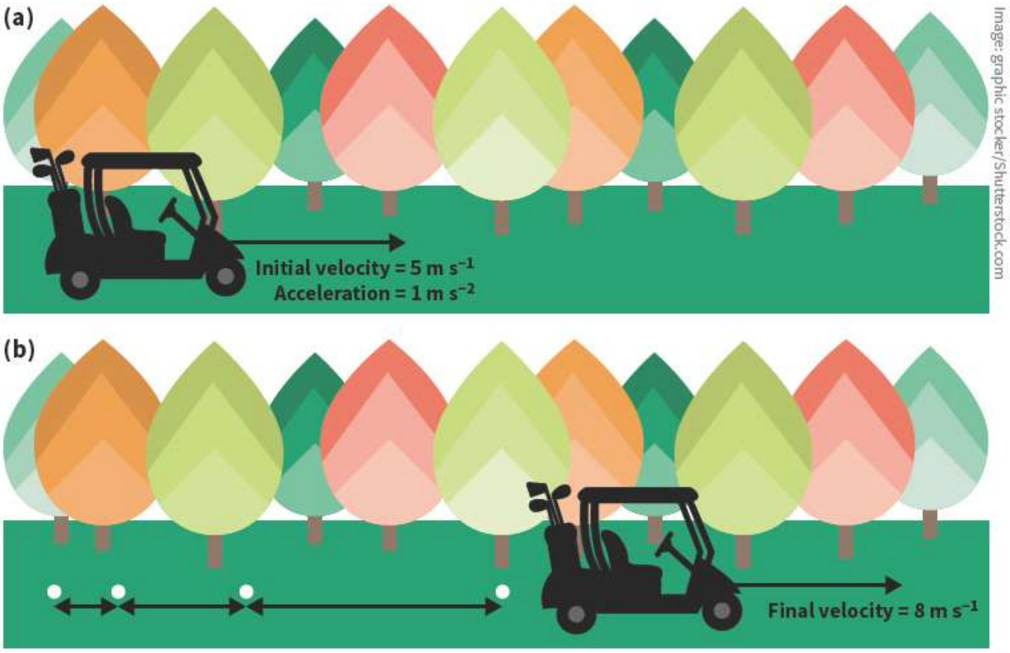


Figure 8 The golf buggy as it travels with an acceleration of 1 m s^{-2}. Note how the distance between each consecutive ball increases.

Here, we can see that as the velocity increases (due to an acceleration of 1 m s^{-2}), the spacing between consecutive golf balls increases.

The average acceleration can be calculated from the following equation. Note that v_1 and v_2 represent the velocity of the object at time t_1 and t_2 respectively.

$$a_{avg} = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

a_{avg} = average acceleration (m s^{-2}), Δv = change in velocity (m s^{-1}), Δt = change in time (s)

Worked example 2

Sonny is running a sprint race. He starts standing still and speeds up at a constant rate over the first four seconds to reach a velocity of 11.0 m s^{-1}. He maintains this velocity for seven seconds and then, having run out of energy, slows down at a constant rate over the next three seconds to a velocity of 7.0 m s^{-1} as he crosses the line.

a **Calculate his acceleration for the first 4.0 s.**

b **Calculate his acceleration for the middle 7.0 s.**

c **Calculate his acceleration for the final 3.0 s.**

Working	Process of thinking
a $a_{avg} = \frac{\Delta v}{\Delta t} = \frac{11.0 - 0}{4.0 - 0} = \frac{11.0}{4.0} = 2.8 \text{ m s}^{-1}$	Use the formula for acceleration and recognise the change in velocity and time from the question.
b $v_2 = 11 \text{ m s}^{-1}, v_1 = 11 \text{ m s}^{-1}$ $a = \frac{\Delta v}{\Delta t} = 0 \text{ m s}^{-2}$	There is no change in velocity over the time interval. This means that there is an acceleration of zero.
c $a = \frac{\Delta v}{\Delta t} = \frac{7.0 - 11.0}{3.0 - 0} = \frac{-4.0}{3.0} = -1.3 \text{ m s}^{-2}$	Substitute in the values for the change of velocity and time as required. Note that the order is important: the final velocity is 7.0 m s^{-1} and therefore must precede the initial velocity of 11.0 m s^{-1}. Here we have defined the positive acceleration as being forwards and negative acceleration as being backwards.

It is important to note the following points:

- Knowing the acceleration does not tell us anything about the specific velocity of the object.
  - It simply tells us how the velocity changes between consecutive time intervals.
  - This means that two objects can have the same acceleration but different velocities and vice-versa.
- Since acceleration is independent from velocity in this way, we must remember that acceleration does not always occur in the direction of motion.
  - When you are braking in a car (i.e the acceleration is backwards), you continue to move forwards.
  - This means that an acceleration equal to zero does not mean that the velocity is also zero and vice-versa.

Unit conversions

In our study of motion, it is important to be able to convert between different units. Whenever we perform calculations to calculate velocity, displacement and time, the units need to be consistent throughout. It is therefore good practice to convert all measurements to SI units. For velocity, this is m s^{-1}, and for displacement, m.

A common conversion that will be required in motion questions is between km h^{-1} and m s^{-1}. To convert from km h^{-1} to m s^{-1}, we divide by 3.6. Conversely, to get from m s^{-1} to km h^{-1}, we multiply by 3.6. For example:

$$72 \text{ km h}^{-1} = \frac{(72 \times 1000) \text{ m}}{(1 \times 3600) \text{ s}} = \frac{72}{1} \times \frac{1000}{3600} \times \frac{\text{m}}{\text{s}} = \frac{72}{3.6} \times \frac{\text{m}}{\text{s}} = 20 \text{ m s}^{-1}$$

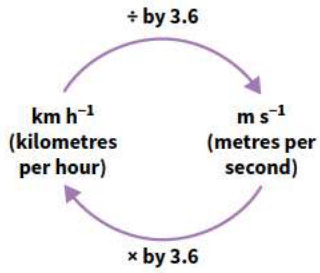


Figure 9 Conversion factors for different velocity/speed units

Theory summary

- Scalars – physical quantities that have only a magnitude (size)
- Vectors – physical quantities that have both magnitude and direction
  - This direction can be communicated through words like 'left' or 'North', angles, or through a positive or negative sign.
- Displacement is the relative change in position of an object, or the shortest distance between its initial and final positions (vector).
  - Distance is the length of the path travelled by an object (scalar).
- Velocity is the rate of change of displacement per unit time (vector).
  - Speed is the rate of change of distance per unit time (scalar).
- Acceleration is the rate of change of velocity per unit time (vector).
  - Acceleration is not necessarily equal to zero just because the velocity at a given time is.
  - Acceleration does not always occur in the same direction as motion.
  - Acceleration occurs whenever velocity changes, even if only the direction of the velocity changes.
- Constant velocity means that the rate at which the displacement of an object changes with respect to time is constant.
  - When this is the case, we can calculate the velocity by calculating the change in position (final minus initial) divided by the size of the time interval in question.

KEEN TO INVESTIGATE?

oPhysics: 'Vector Addition' simulation
ophysics.com/k1.html

oPhysics: 'Vector Addition and Subtraction' simulation
ophysics.com/k2.html

YouTube video: Doc Schuster – Visualize How Acceleration Affects Velocity and Speed
youtu.be/4_iOLZvbgrE

CONCEPT DISCUSSION QUESTION

Consider a sports car and a large truck stopped at a red light. When the light turns green and both vehicles start moving, we could reasonably expect the sports car to reach the next set of lights first because the sports car is 'faster', even though both vehicles reach (but do not exceed) the speed limit . Discuss what we mean by 'faster' in this context and how this explains the expected observation from this scenario.

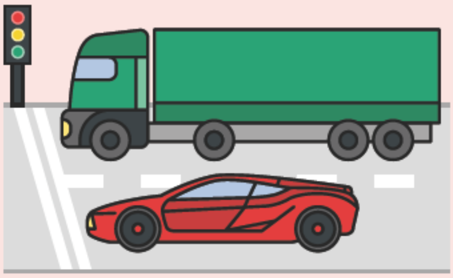


Image: Daiquiri/Shutterstock.com

Answers on page 507

Hints

If the sports car reaches the next set of lights before the truck, what can we say about the average speed of the sports car compared to the truck as they drive between the two sets of lights?

How can we explain this, given that they both reach the same maximum speed?

Which physical property describes this difference in the two vehicles' motion?

8A Questions

THEORY REVIEW QUESTIONS

Question 1

Kenneth, having just purchased a new pair of sneakers, decides to go for a walk. He travels 8 km east and then 6 km north.

He claims that from his starting point, his displacement is 14 km. Is he correct?

A Yes, because displacement is given by the total length he has covered.

B Yes, because he has not changed directions on his walk and therefore displacement is the same as distance travelled.

C Partially, but he would have to include a direction because displacement is a vector.

D No, because his direction has changed and he cannot simply add the two lengths.

E No, because we would need to know his velocity to find his displacement.

Question 2

In which of the following scenarios would the average speed and average velocity (calculated from start to finish) be different? *(Select all that apply)*

I A 100 m runner starts the race, takes a 30 second break, then finishes the race.

II A 400 m runner completes his race, one full lap around the track.

III A travelling tourist takes the round-trip train line from Paris to Rome and back.

IV An object moves 25 metres in a straight line but slows down and speeds up along the way.

Question 3

Fill in the gaps in the following paragraph to correctly show the relationship between the variables of motion covered in this lesson.

__________ (displacement/velocity/distance) is a measure of the change in position of an object. The variable that measures how the displacement changes over time is __________ (acceleration/speed/velocity). Unlike __________ (speed/acceleration), this variable is a vector. In order to calculate the average acceleration, we divide the change in __________ (displacement/time/velocity) by the change in __________ (speed/time/displacement).

[redacted]

Question 4

This lesson explored a golf buggy dropping a golf ball behind it every second as it travelled along. Under this analogy, match the image to the description that fits best. Each image may be used more than once or not at all.

	Description of motion
I	A golf cart with an acceleration of 0 m s^{-2}
II	A golf cart with a comparatively large positive acceleration
III	A golf cart travelling at constant velocity
IV	A golf cart with a non-zero initial velocity but a small positive acceleration
V	A golf cart with negative acceleration
VI	A golf cart with a constant speed but non-constant velocity

A

B

C

D

E

DECONSTRUCTED EXAM-STYLE QUESTION

Question 5 (5 MARKS)

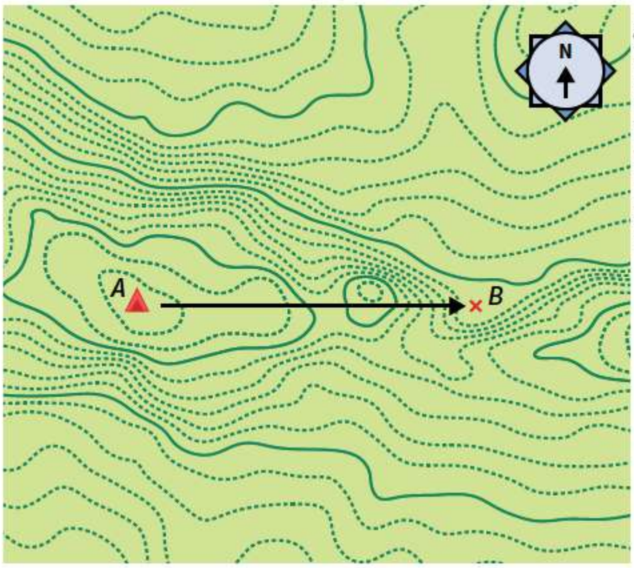


Image: Modulo18/Shutterstock.com

Michael and Tara are going for a hike. They travel from their camp at point *A* to another campsite at point *B*.

- The journey takes 9.0 hours in total.
- They walk at an average velocity of 4.0 m s^{-1} up hills and 6.0 m s^{-1} on flat ground.
- They stop for a 1 hour break at some point in the hike.
- The distance they hike up hills is half the distance they hike on flat ground.

Use this information to find their average velocity for the entire hike.

Prompts

a We can split the journey up into two parts: the time spent walking up hills (t_{hills}) and the time spent walking on flat ground (t_{flat}). Which of the following gives the correct expression for t_{flat}?

A $\frac{40}{6} = 6.7$ hours

B $\frac{s_{flat}}{6.0}$

C $\frac{s_{flat}}{4.0 + 6.0} = \frac{s_{flat}}{10}$

D There is not enough information to determine this.

b Which of the following gives the correct expression for t_{hills}?

A $\frac{40}{6.0} = 6.7$ hours

B $\frac{40}{4.0} = 10$ hours

C $\frac{s_{hills}}{v_{hills}} = \frac{s_{hills}}{4.0}$

D There is not enough information to determine this.

c Which of the following correctly expresses the total time of the trip in terms of t_{flat} and t_{hills}?

A $9.0 = t_{flat} - t_{hills}$

B $9.0 = t_{hills} - t_{flat} - 1$

C $9.0 = t_{hills} + t_{flat}$

D $9.0 = t_{hills} + t_{flat} + 1$

d The question states that the distance they hike up hills is half the distance they hike on flat ground. Use this information to identify the equation below that correctly relates t_{flat} to s_{hills}.

A $t_{flat} = \frac{2 \times s_{hills}}{6.0} = \frac{s_{hills}}{3.0}$

B $t_{flat} = \frac{0.5 \times s_{hills}}{6.0} = \frac{s_{hills}}{12.0}$

e Combine the equations from parts **b-d** to find the values of s_{hills} and s_{flat} from the list below.

A 8.1 km, 16 km

B 14 km, 27 km

C 24 km, 48 km

D 6.6 km, 13 km

Question

f Calculate the average velocity for the entire hike. (5 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

A man runs 100 metres along a straight path. If it takes him 20 seconds to complete, what is the magnitude of his average velocity?

Question 7 (3 MARKS)

Jessica swims up and back along a 25 metre lap pool in 40 seconds.

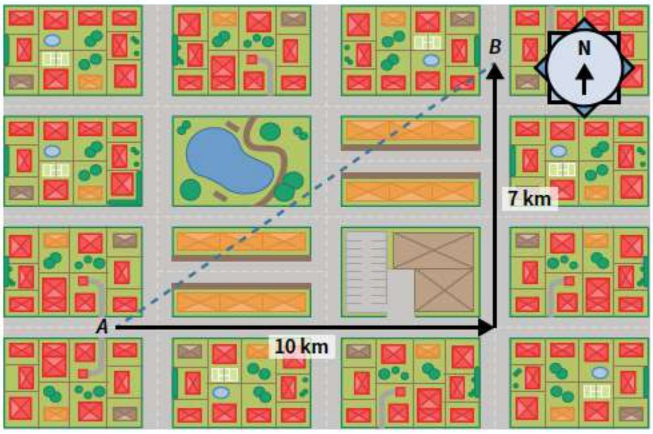
a What is her distance travelled? (1 MARK)

b What is her displacement? (1 MARK)

c What is her average velocity? (1 MARK)

Question 8 (3 MARKS)

Sarah goes for a walk as shown in the diagram below.



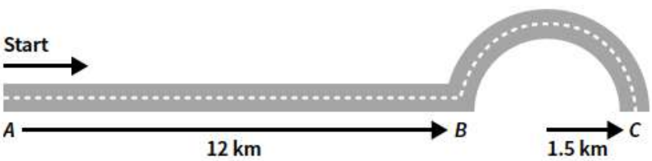
If this journey takes Sarah 100 minutes, calculate the magnitude of her average velocity in km h^{-1} as she walks from *A* to *B*.

Question 9 (3 MARKS)

Describe the similarities and differences between velocity and speed, making sure to discuss when their magnitudes are equal or different.

Use the following information to answer Questions 10 and 11.

A fairly reckless individual drives a car in a straight line at a constant speed of 60 km h^{-1} from *A* to *B*, then at a different constant speed from *B* to *C* around a circular track as shown below.



Question 10 (2 MARKS)

How long, in seconds, will it take for them to travel from *A* to *B*?

Question 11 (7 MARKS)

a Consider the motion of the car between points *B* and *C*. Instead of a speed limit, there is an 'average velocity limit' of 100 km h^{-1} whilst rounding the bend *BC*. If it takes the driver 100 seconds to complete the turn, determine whether or not they will exceed the limit. (4 MARKS)

b The reckless individual drives around the track from *B* to *C* at a constant speed. However, this is different to the magnitude of their average velocity over this stretch. Explain why this is, using calculations to support your answer. (3 MARKS)

Question 12 (8 MARKS)

Hansel and Gretel are running through the forest trying to find their way out. So that they can retrace their footsteps if necessary, they leave behind a breadcrumb every second on the ground behind them.

Use the information below to construct sketches on a separate piece of paper (like the golf-cart scenarios) of Hansel and Gretel's motion and decide (with justification, no calculations required) in which cases there is non-zero acceleration. Assume they drop a breadcrumb every second.

Description	Sketch	Non-zero acceleration?
They start stationary and run along a straight path to reach a velocity of 10 m s^{-1} after 4 seconds		
They travel 30 metres east and then 40 metres north at a fixed speed of 10 m s^{-1}		
They run with a constant speed around a semicircular path with a radius of 10 metres in 5 seconds		
They slow down from 10 m s^{-1} to 5 m s^{-1} in a straight line over 5 seconds as they near the end of the path		

Previous lessons

Question 13 (4 MARKS)

Jeffrey is constructing a home-theatre system and needs to cut some copper wire ($\rho = 1.724 \times 10^{-8}\ \Omega\ \text{m}$) to connect the speakers. The speakers are to be connected by a length of wire 20 metres long. If the speakers operate correctly when the wire has a resistance of 8 Ω, what radius of wire should Jeffrey select?

Question 14 (3 MARKS)

List one of the three types of radioactive decay that we can detect and identify its composition as well as its relative ionisation and penetration ability compared to the other forms of nuclear decay.

Key science skills

Question 15 (5 MARKS)

You are provided with the following data points which describe the displacement of a car driving along a straight track of road for a given length of time:

Time (seconds)	0.8	1.4	6.0	9.0
Displacement (metres)	24.0	56.0	226	316

a Plot the data on a graph of displacement against time. Include a line of best fit. (3 MARKS)

b Calculate the gradient of your line of best fit. What does this gradient represent? (2 MARKS)

8B GRAPHING MOTION

In the previous lesson, we examined motion with constant velocity or acceleration. We will now move on to how we graph, and read graphs, of this type of motion. This will allow us to describe and analyse the relationships between displacement, velocity, acceleration and time in more useful ways.

8A Describing motion	8B Graphing motion	8C The constant acceleration equations

Study design dot point

- graphically analyse non-uniform motion in a straight line

Key knowledge units

Graphing motion with constant velocity	2.1.3.1
Graphing motion with constant (non-zero) acceleration	2.1.3.2

Formulas for this lesson

Previous lessons		New formulas
8A	$speed = \frac{distance}{time}$	No new formulas for this lesson
8A	$v_{avg} = \frac{\Delta s}{\Delta t}$	
8A	$a_{avg} = \frac{\Delta v}{\Delta t}$	

Definitions for this lesson

average acceleration the average rate of change of velocity per unit time over a given period (vector quantity)

average velocity the average rate of change of displacement per unit time over a given period (vector quantity)

instantaneous acceleration the rate of change of velocity per unit time at a single instant in time (vector quantity)

instantaneous velocity the rate of change of displacement per unit time at a single instant in time (vector quantity)

Graphing motion with constant velocity 2.1.3.1

OVERVIEW

Graphing motion allows us to analyse displacement, velocity and acceleration over a range of time periods. Instantaneous speed and velocity describe the movement of an object at a single instant in time.

THEORY DETAILS

Introduction to motion graphs

Graphing motion is the process of extrapolating relationships between displacement, velocity and acceleration so we can analyse the behaviour of a moving object over a period of time. Suppose we knew that an object was travelling at a constant velocity and we knew its displacement after every 2 seconds. Then we can produce a linear relationship between its displacement and time as shown in Figure 1.

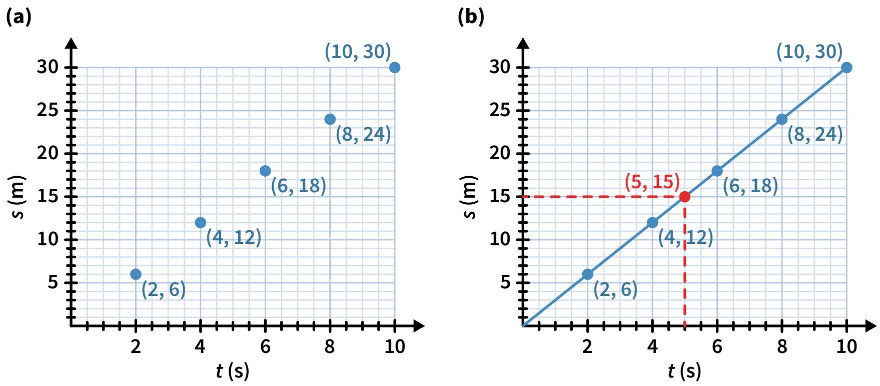


Figure 1 **(a)** The displacement of the object at 2 second intervals and **(b)** the line which shows its displacement at every instant of time from $t = 0$ to $t = 10$.

The vertical axis represents the displacement in metres and the horizontal axis represents the time in seconds. If we want to know the displacement of the golf cart at any point in time, we would:

- find the time value on the horizontal axis,
- trace upwards until we meet the graph,
- trace across and read off the displacement value on the vertical axis.

This is shown by the dotted red lines in Figure 1(b). At a time of 5 seconds the object has a displacement of 15 m.

Features of displacement-time graphs

For objects travelling at a constant velocity, we model their motion on a displacement-time graph as a straight line.

In Figure 2, the gradient between the points (t_1, s_1) and (t_2, s_2) is given by $\frac{s_2 - s_1}{t_2 - t_1} = \frac{\Delta s}{\Delta t}$. Recall from Lesson 8A that this is equal to the average velocity $v_{avg} = \frac{\Delta s}{\Delta t}$. Therefore we can conclude that the gradient between two points of a displacement-time graph is the **average velocity** between these two points. Because of this relationship, for objects with constant velocity, the gradient of the displacement-time graph must also be constant.

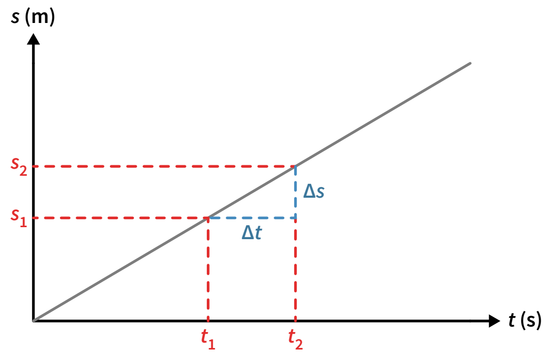


Figure 2 The gradient of a displacement-time graph gives the average velocity.

Instantaneous speed and velocity

The instantaneous velocity tells us the rate at which displacement is changing at a single point in time. It is a vector quantity and is often not equal to the average velocity for the entire journey. The two are equal only when the acceleration is zero.

Imagine you are driving along in a car from one place to another. You could calculate your average speed as the distance travelled divided by the time taken, for example, 40 km h^{-1}. In this analogy, your instantaneous speed at a particular moment would be what the speedometer is showing at that time.

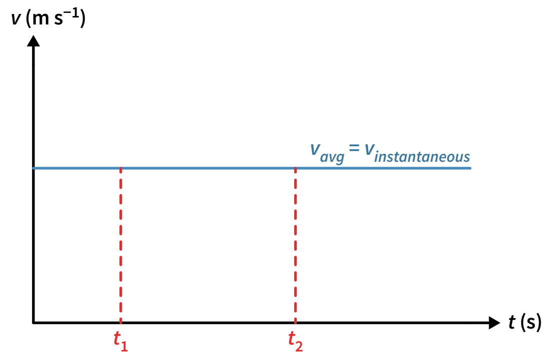


Figure 3 The velocity-time graph of an object travelling at a constant velocity will be a horizontal line.

Velocity-time graphs

A velocity-time graph is the line produced when we plot the instantaneous velocities of an object at each instant over a given time interval. Here, the velocities are on the vertical axis and time is on the horizontal axis.

For an object travelling at a constant velocity (when $a = 0$ m s^{-2}) this graph will be a horizontal line as shown in Figure 3.

The gradient for a velocity-time graph is equal to the acceleration of the object. This is because $gradient = \frac{rise}{run} = \frac{\Delta v}{\Delta t}$, which is equal to our formula for calculating the average acceleration.

The area under a velocity-time graph between two time values is equal to the change in displacement over that interval (see Figure 4).

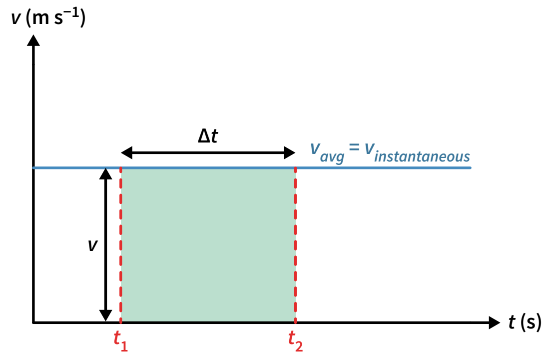


Figure 4 The area under a velocity-time graph gives the change in displacement.

The green area under the graph is a rectangle with an area given by *height* × *width* = $v \times \Delta t$. Comparing this to the equation for calculating velocity, $v = \frac{\Delta s}{\Delta t}$ rearranged to form $\Delta s = v \times \Delta t$, we can see that the area is equal to the change in displacement.

Graphing motion with constant (non-zero) acceleration 2.1.3.2

OVERVIEW

At constant, non-zero acceleration, the graph of velocity-time is linear. The acceleration-time graph can be used to determine the change in velocity. Motion graphs can be used to model objects in vertical free fall.

THEORY DETAILS

Velocity-time graphs (constant, non-zero acceleration)

For an object travelling with constant, non-zero acceleration, its graph of velocity-time will be linear.

In Figure 5, the gradient between the points (t_1, v_1) and (t_2, v_2) is given by $\frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}$. This expression is equal to the formula for average acceleration, $a_{avg} = \frac{\Delta v}{\Delta t}$. As the acceleration is constant, the graph must be a straight line since the gradient must be equal between any two points.

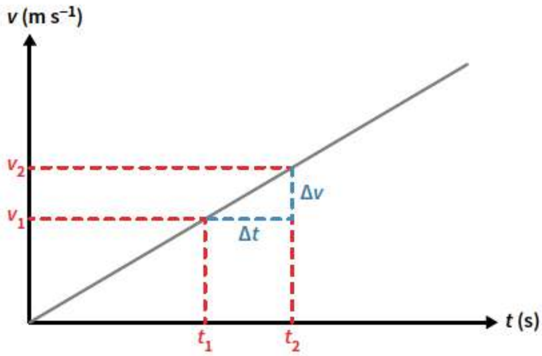


Figure 5 The gradient of a velocity-time graph is equal to the average acceleration.

In the case of constant velocity, the gradient of a displacement-time graph is equal to both the average and instantaneous velocity. A similar property applies to constant acceleration and velocity-time graphs. The gradient of the velocity-time graph is equal to both the average acceleration and the instantaneous acceleration, the rate at which the velocity is changing at a single moment of time.

For an object travelling at a constant velocity, we learned that the area under a velocity-time graph is equal to the change in displacement. This result is still true, even when the acceleration is non-zero.

We calculate the change in displacement under constant non-zero acceleration in the same way we did under constant velocity, with one exception. Since displacement is a vector, to calculate the change in displacement we add the area above the horizontal axis and subtract the area below it (in Figure 6, $A_1 - A_2$). This is known as the signed area under the graph (or curve). As distance is a scalar quantity, it will be equal to the sum of the areas (in Figure 6, $A_1 + A_2$).

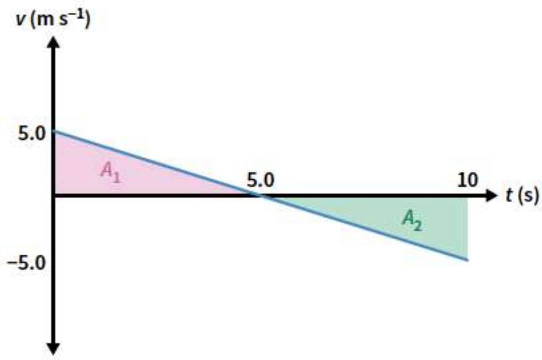
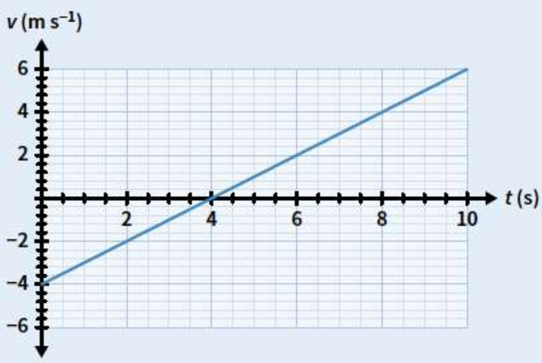


Figure 6 The change in displacement is equal to the area above the horizontal axis minus the area below the horizontal axis.

Worked example 1

A soccer player during a match produces the following velocity-time graph for a given 10 second interval:



a **What is the magnitude of their average acceleration?**

b **What is their change in displacement over the 10 seconds?**

[redacted]

Working

a $a_{avg} = \frac{\Delta v}{\Delta t} = \frac{rise}{run} = gradient$

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{6-(-4)}{10-0} = 1 \text{ m s}^{-2}$

$\therefore a_{avg} = 1 \text{ m s}^{-2}$

The magnitude of their average acceleration is 1 m s^{-2}.

Process of thinking

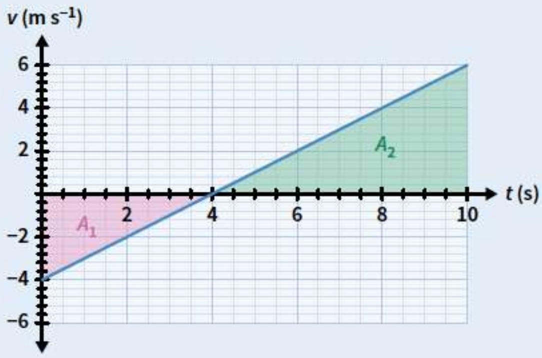
Recall that the gradient of a velocity-time graph for constant acceleration is equal to the average acceleration.

Calculate gradient using two points on the graph. Here they are (10, 6) and (0, −4).

Answer in the context of the question. No direction is required because the question asked for the magnitude of the average acceleration.

b $\Delta s = signed\ area\ under\ graph = A_2 - A_1$

Recall that the signed area under a velocity-time graph is equal to the change in displacement.



$signed\ area = A_2 - A_1 = \left(\frac{1}{2} \times 6 \times 6\right) - \left(\frac{1}{2} \times 4 \times 4\right) = 10 \text{ m}$

The signed area under the graph is equal to the area above the horizontal axis minus the area below the horizontal axis.

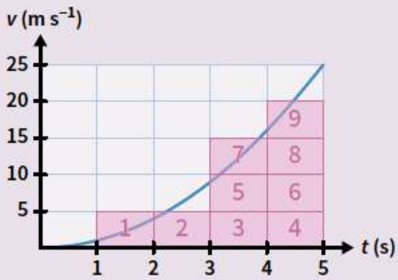
The soccer player's change in displacement is 10 m in the positive direction.

Answer in the context of the question, making sure to provide a direction.

In VCE Physics you will be asked to approximate the area under curved graphs. This process allows us to find the change in displacement and velocity from a velocity-time graph and acceleration-time graph respectively when we are dealing with things like parabolic instead of linear relationships.

PROBLEM SOLVING PROCESS

Use this technique if the graph includes grid lines and the region under the line is non-linear (not easily divided into simple triangles and rectangles).



1. Count the number of whole squares under the line.
2. For all remaining squares, use the following rule:
   - **If more than 50%** of a square is under the line, include the whole square (squares 1 and 7).
   - **If less than 50%** of a square is under the line, exclude the whole square.
3. Calculate the area of one square.
   - Here, each square has dimensions of 5 m s^{-1} × 1 s = 5 m.
4. Multiply the total number of squares by the area of one square.
   - $\Delta s = 9 \times 5 = 45$ m

Acceleration-time graphs

If we consider the value of the instantaneous acceleration at every point in time, we can construct an acceleration-time graph, with the acceleration on the vertical axis and the time on the horizontal axis. For an object with constant acceleration, the acceleration-time graph will be a horizontal line as in Figure 7.

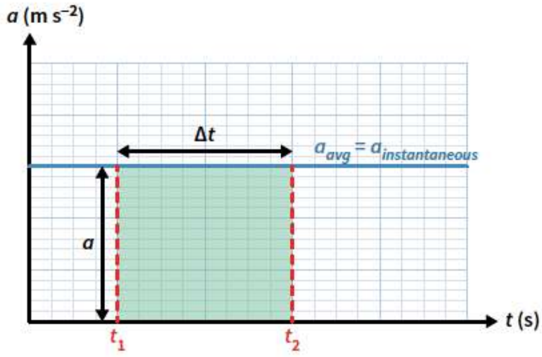


Figure 7 The area under an acceleration-time graph is equal to the change in velocity.

The key features to note are that:

- The gradient of the graph is zero, indicating constant acceleration.
- The average acceleration is equal to the instantaneous acceleration.
  - Both of these values are equal to the gradient of the object's velocity-time graph.
- The area under the line between t_1 and t_2 is equal to the change in velocity over that time interval.
  - The area is equal to *height* × *width* = $a \times \Delta t = \Delta v$ which can be derived by rearranging the formula used to define acceleration, $a = \frac{\Delta v}{\Delta t}$.

Graphs of vertical motion

Up to this point, we have only considered graphs of horizontal motion. However, we can also use them to model vertical motion.

In later lessons, we will see that all objects in free fall are subject to a constant acceleration due to gravity, g, which has a value of 9.8 m s^{-2} downwards close to the surface of the Earth. Because objects in free fall do not travel with a constant velocity, this lesson will not consider the displacement-time graphs of such motion. The relationships regarding gradients and areas of each graph previously outlined still apply.

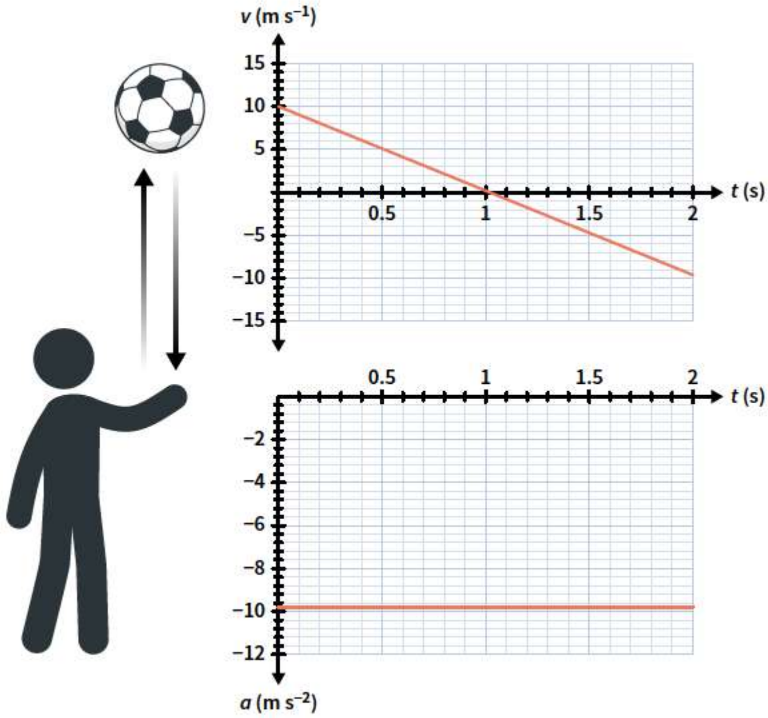
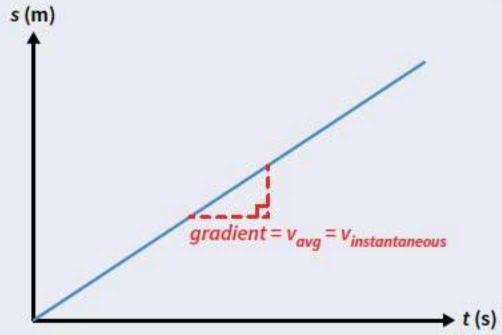
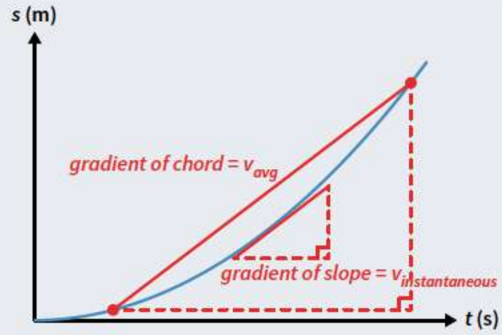
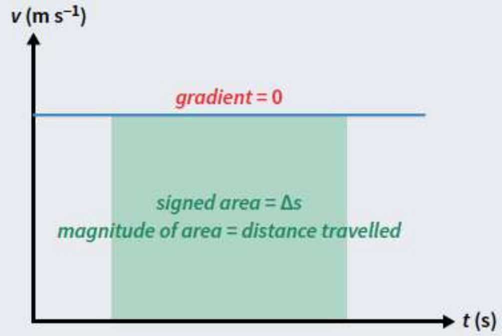
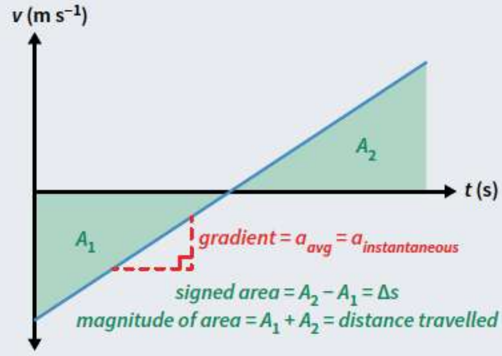
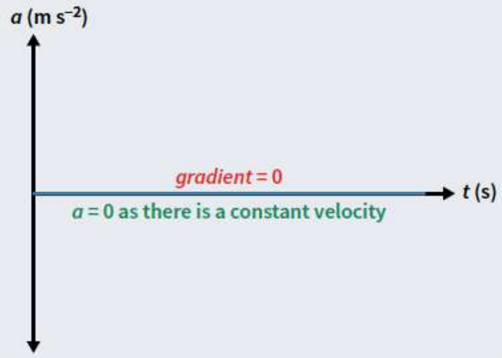
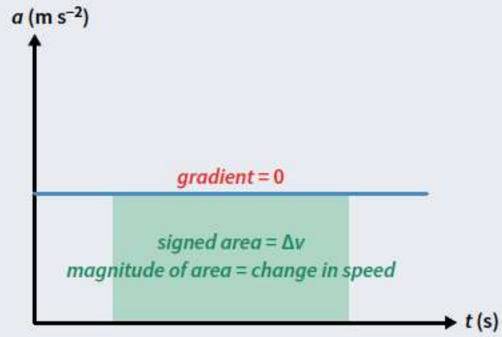


Figure 8 The velocity-time and acceleration-time graph of a ball thrown upwards with an initial upwards velocity of 10 m s^{-1}.

Since average acceleration is equal to the gradient of the velocity-time graph, this means that the gradients of all velocity-time graphs for objects in free fall are equal to −9.8, the acceleration due to gravity. Note that this assumes the graph is given in SI units of s and m s^{-1}.

Theory summary

- It is important to distinguish between instantaneous and average measures of motion:
  - Instantaneous velocity is equal to average velocity only if the acceleration is zero.
  - Instantaneous acceleration is equal to average acceleration only if the acceleration is constant.

	Constant velocity (non-zero)	Constant acceleration (non-zero)
Displacement-time graphs		
Velocity-time graphs		
Acceleration-time graphs		

KEEN TO INVESTIGATE?

oPhysics 'Kinematics in 1D: Velocity vs Time Graphs' simulation
ophysics.com/k5a.html

oPhysics 'Kinematics in One Dimension: Two Object System' simulation
ophysics.com/k7.html

oPhysics 'Position, Velocity, and Acceleration vs Time Graphs' simulation
ophysics.com/k4b.html

oPhysics 'Uniform Acceleration in One Dimension: Motion Graphs' simulation
ophysics.com/k4.html

CONCEPT DISCUSSION QUESTION

When an object falls from a great height, the magnitude of its downward acceleration is approximately equal to 9.8 m s^{-2}. However, repeated collisions with air molecules as it falls will reduce the object's acceleration until it reaches 0 m s^{-2}. This is why there is a limit to the velocity at which objects can fall on Earth, otherwise known as terminal velocity.

Using this information, discuss what the acceleration-time graph and velocity-time graph of a basketball would look like if it were dropped from the top of a tall building and accelerated towards its terminal velocity.

Answers on page 507

Hints

Is there a difference in the change in velocity during the initial few seconds of falling and the change in velocity near terminal velocity? How might we represent this on the velocity-time graph?

If the velocity of the basketball is approaching a limit, what does this tell us about the magnitude of the acceleration at this point?

What is the link between the acceleration-time graph and the velocity-time graph?

8B Questions

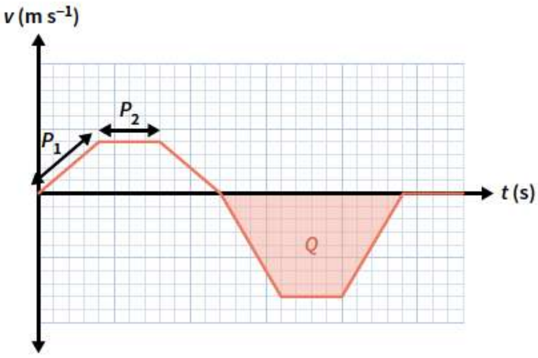
THEORY REVIEW QUESTIONS

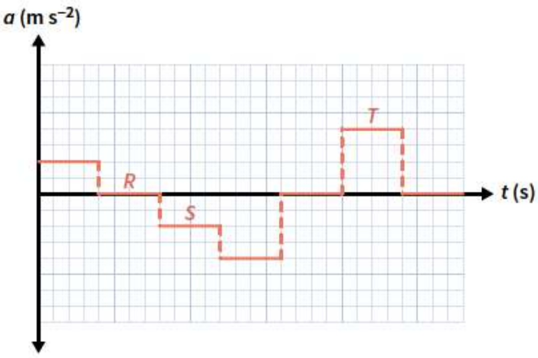
Question 1

Fill in the gaps in the following paragraph to describe the relationship between motion graphs.

The gradients of a velocity-time graph and a displacement-time are equal to the average __________ (velocity/acceleration/speed) and __________ (displacement/velocity/change in time) respectively. A negative acceleration therefore __________ (has to/does not have to) correspond to a negative velocity on a velocity-time graph.

Use the following information to answer Questions 2 and 3.





Question 2

Which of the following statements are true for the velocity-time graph? *(Select all that apply)*

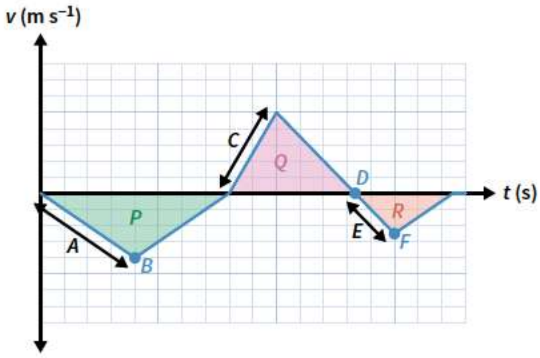
- **I** The instantaneous velocities over P_1 are all equal to the average velocity over that interval.
- **II** The instantaneous velocities over P_2 are all equal to the average velocity over that interval.
- **III** The magnitude of the shaded area Q represents the distance travelled over that time interval.
- **IV** The object is furthest away from its starting location at P_2.

Question 3

Which of the following statements are true for the acceleration-time graph? *(Select all that apply)*

- **I** The acceleration for interval R being equal to zero does not mean that the velocity at this moment must also be zero.
- **II** The acceleration at point S is negative, which means that the object is travelling backwards/in the negative direction.
- **III** The acceleration along interval T is positive, which means that the object will begin moving faster.

Use the following graph to answer Questions 4 and 5.



Question 4

Match the points or time intervals (*A*–*F*) on the graph to each of the following descriptions.

- **a** The part(s) of the graph where the object changes direction
- **b** The part(s) of the graph where the object has maximum positive acceleration
- **c** The part(s) of the graph where the acceleration is negative
- **d** The part(s) of the graph where the acceleration goes from negative to positive

Question 5

Which of the following expressions involving the areas P, Q and R gives the correct value for the change in displacement and distance travelled over the entire time of motion?

	Change in displacement	Distance travelled
A	$P - Q + R$	$P - Q + R$
B	$Q - P - R$	$P + Q + R$
C	$P + Q + R$	$Q - P - R$
D	$P - Q + R$	$P + Q + R$

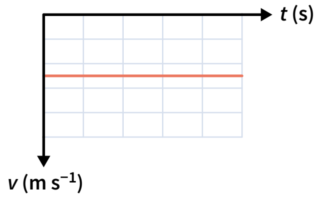
Question 6

For each of the displacement-time graphs, choose the correct corresponding velocity-time graph.

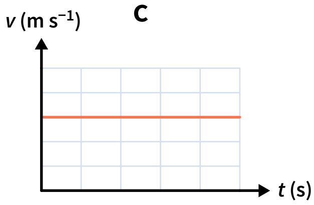
Velocity-time graphs

A

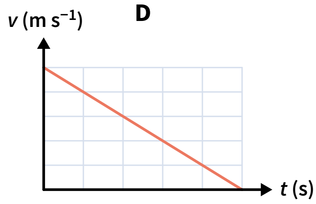
B



C

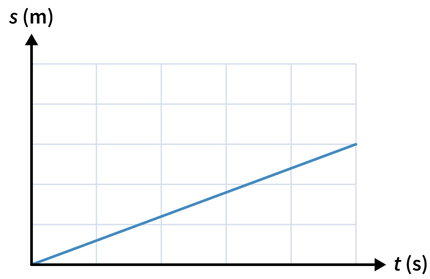


D

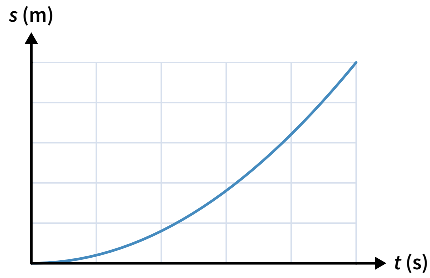


Displacement-time graphs

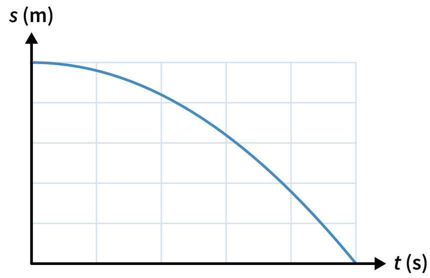
a



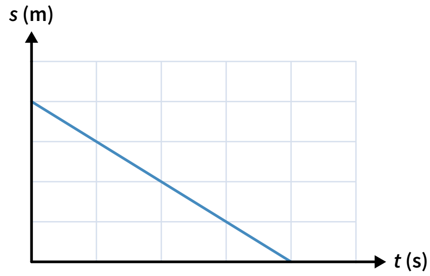
b



c

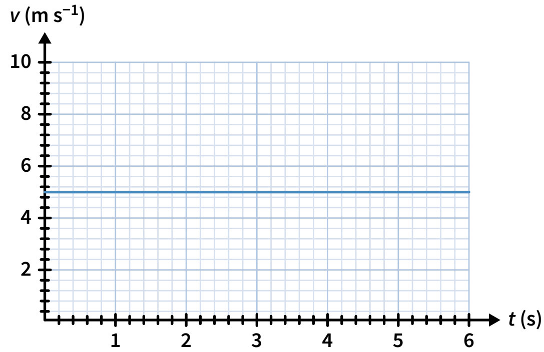


d

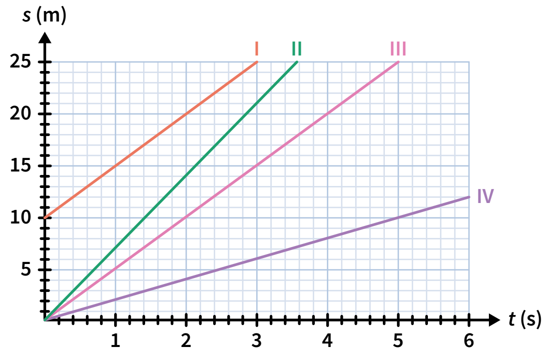


Question 7

Consider the velocity-time graph shown below.



To which of the following lines on the displacement-time graph could this correspond? *(Select all that apply)*



DECONSTRUCTED EXAM-STYLE QUESTION

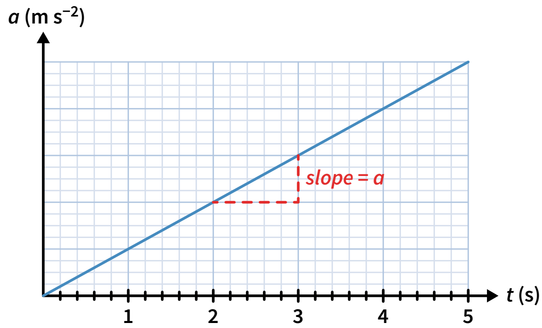
Question 8 (4 MARKS)

An F1 driver in the Australian Grand Prix starts the race from rest and accelerates along a straight section of the track at a constant rate of a m s^{-2}.

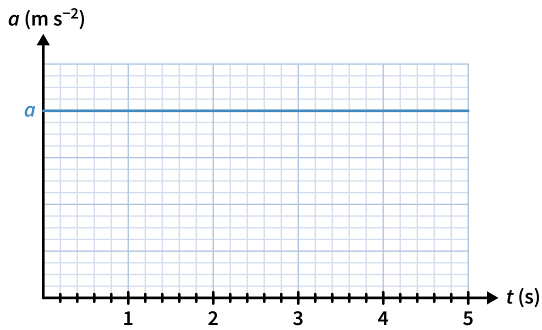
Prompts

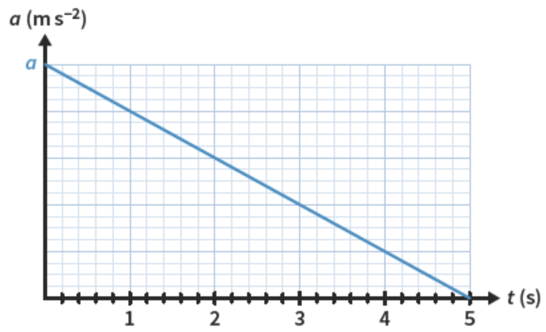
a Which of the following gives the acceleration-time graph over the first 5 seconds?

A



B



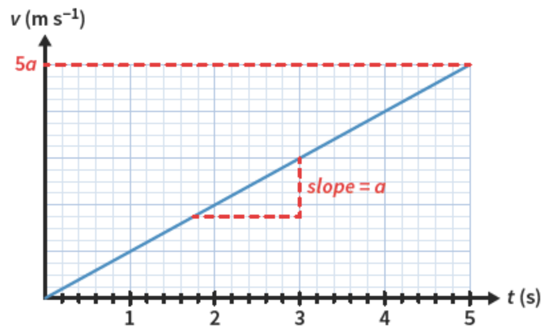
C


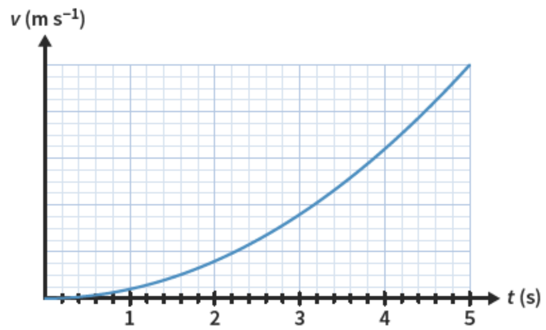
b What is the change in velocity of the car over the first 5 seconds in terms of a?

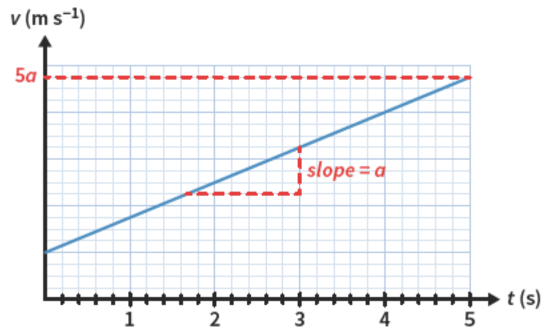
A $\Delta v = \frac{1}{2} \times 5 \times a$ **B** $\Delta v = \frac{1}{2} \times a^2$

C $\Delta v = 5a$

c Which of the following graphs correctly shows the velocity-time graph of the car?

A


B


C


d What is the displacement of the car in terms of a over the 5 seconds?

A $\Delta s = 5a \times \Delta t = 25a$

B $\Delta s = \frac{1}{2} \times 5a \times 5 = 12.5a$

C $\Delta s = \frac{1}{2} \times (v_f + 5a) \times 5$

D The displacement-time graph is parabolic, so we could only approximate the change in displacement.

Question

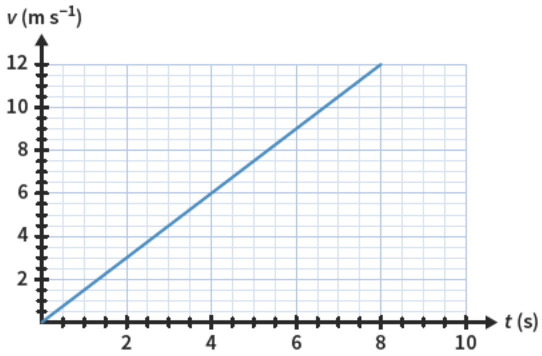
e Calculate the value of a so that the F1 driver covers the first 150 metres of the race in 5 seconds. (4 MARKS)

EXAM-STYLE QUESTIONS

This Lesson

Question 9 (2 MARKS)

Consider the following displacement-time graph.

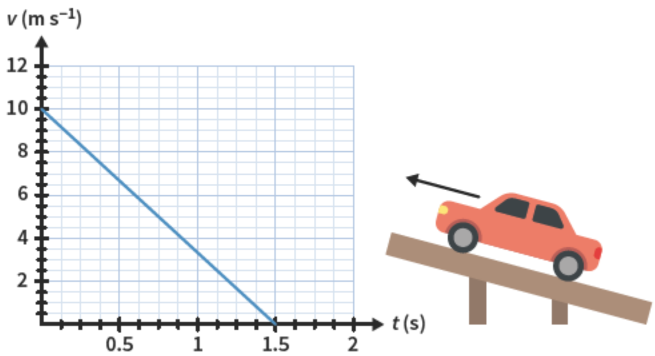


a Calculate the magnitude of the average velocity. (1 MARK)

b Calculate the magnitude of the instantaneous velocity at $t = 4$ s. (1 MARK)

Question 10 (3 MARKS)

Rachel's physics class is using ticker timers to analyse the motion of model cars rolling up a ramp. The velocity-time graph of her car in the direction of the ramp is shown below:

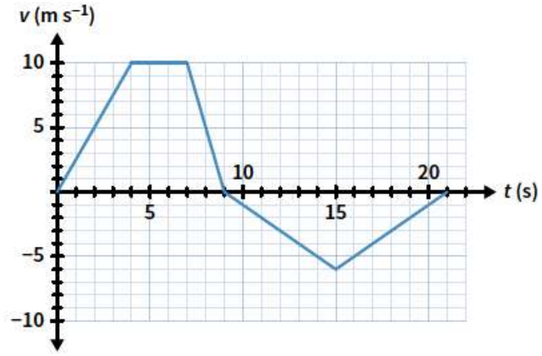


a What is the magnitude of the car's acceleration? (1 MARK)

b What is the change of the displacement of the car before it comes to a stop and starts to roll back down the ramp? (2 MARKS)

Question 11 (3 MARKS)

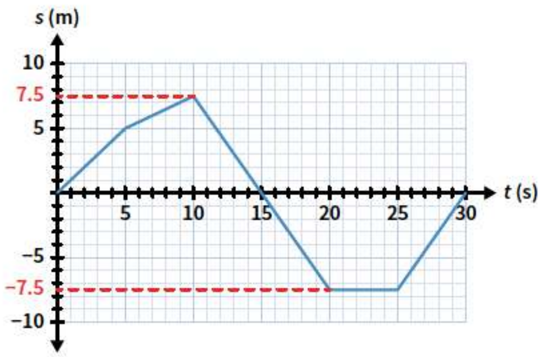
Kate is doing some warm-up runs along a straight track before her race. She sprints out, turns around, and then jogs back. Her velocity-time graph for one of these warm-up sprints is shown below.



By calculating her change in displacement, determine how far away Kate finishes from where she started.

Question 12 (4 MARKS)

Dumbledore spends most of his days strolling back and forth in his office. Given his old age and his 'excitable' nature, his movement is fairly irregular and his displacement-time graph for a period of his day looks like this.



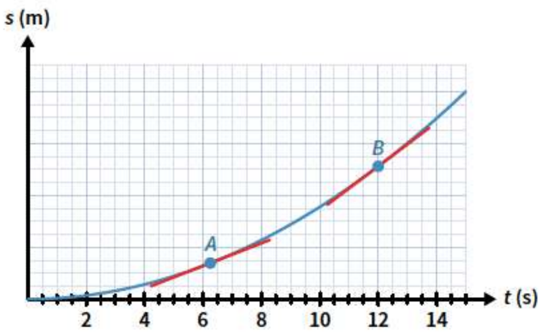
a Calculate the magnitude of his average velocity from $t = 0$ to $t = 10$ seconds. (1 MARK)

b Calculate the magnitude of his average velocity from $t = 0$ to $t = 30$ seconds. (1 MARK)

c Calculate his average speed from $t = 0$ to $t = 30$ seconds. (2 MARKS)

Question 13 (5 MARKS)

Tanya gets a new pair of rollerblades for Christmas and decides to roll down a steep hill. Her displacement-time graph can be modelled by the following parabola.

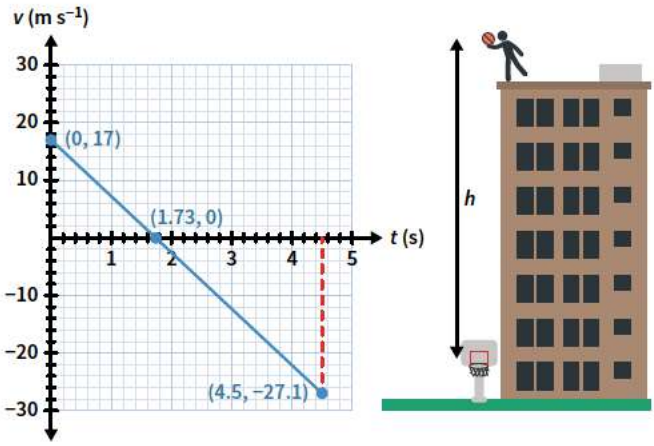


a The slope of the curve at A ($t = 6.0$ s) is equal to 4.5 and at B ($t = 12$ s) is equal to 9.0. Use this information to sketch her velocity-time graph. (3 MARKS)

b Hence calculate the magnitude of her change in displacement from point A to point B. (2 MARKS)

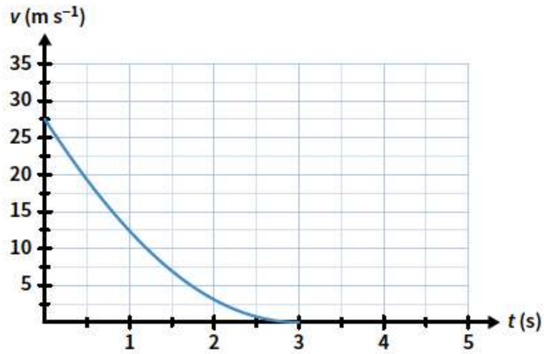
Question 14 (3 MARKS)

Stevie is trying to make a basketball trick shot by shooting a ball vertically off the top of a tall tower. Use the velocity-time graph to calculate the height, h, from where the ball is released to the hoop below. Assume that air resistance was observed to be negligible and that the ball lands in the hoop 4.5 s after it was released. Take up to be positive.



Question 15 (3 MARKS)

A car company is testing how well their new car can brake by having it decelerate from a high speed to stationary. Once the brakes are applied, the car needs to be able to stop over a maximum distance of 35 metres. The velocity-time graph of the car from its test is shown below.



By approximating the area under the curve, determine whether or not the car passed the test.

Question 16 (6 MARKS)

Joaquin is having a bike race with his friend Tony, and decides to give him a head start. Tony rides away at a constant speed of 12.5 m s^{-1}. After 4 seconds, Joaquin begins to ride after him. He accelerates for 5 seconds at 3 m s^{-2}, before continuing on at a constant speed.

a Draw the speed-time graphs for both Joaquin and Tony on the one axis. (3 MARKS)

b Use the graphs to calculate how long it takes before Joaquin catches up to Tony. (3 MARKS)

Question 17 (5 MARKS)

Gracie is trying to figure out how high she can throw a ball in the air. She throws the ball with an initial velocity of 14.0 m s^{-1}. Take acceleration due to gravity, g, to be −9.8 m s^{-2} and assume that the effects of air resistance are negligible.

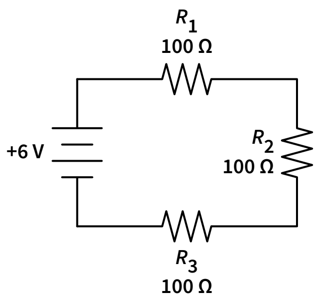
a Sketch a velocity-time graph to model Gracie's throw. (3 MARKS)

b Use the graph to calculate the maximum height of her throw. (2 MARKS)

Previous lessons

Question 18 (7 MARKS)

Lawrence is analysing power loss in a basic series circuit. He begins with the following configuration:



a Calculate the current across the resistor R_1. (2 MARKS)

b Calculate the power dissipated across R_1. (2 MARKS)

c Lawrence now removes resistor R_3 and reconnects the circuit. What is the ratio between the power dissipated across R_1 in the new configuration to the old one? (3 MARKS)

Question 19 (2 MARKS)

Hydrogen bombs rely on the fusion of lithium-6 (m = 9.988 × 10^{-27} kg) and deuterium (m = 3.344 × 10^{-27} kg) into two helium nuclei (m = 6.646 × 10^{-27} kg per nuclei). Calculate the energy released when one lithium-6 atom and one deuterium atom undergo nuclear fusion.

Key science skills

Question 20 (4 MARKS)

Juzzy is using a speed-gun to calculate the acceleration of a car that is driving directly towards him. He records the following measurements:

Instantaneous velocity (m s^{-1})	5.4	8.3	12.0	17.1	22.2
Time (s)	1.4	2.3	3.5	4.6	5.9

There is an uncertainty in the speed-gun of ±1.5 m s^{-1}. Use the data points to plot a graph of velocity against time. Include a line of best fit.

8C THE CONSTANT ACCELERATION EQUATIONS

In the previous lesson, we learned how to analyse motion using graphs. However, motion can also be described by a series of equations. In this lesson we will discuss and derive the so-called constant acceleration equations and investigate how they help us describe motion.

8A Describing motion	8B Graphing motion	8C The constant acceleration equations

Study design dot point

- analyse graphically, numerically and algebraically, straight-line motion under constant acceleration: $v = u + at, v^2 = u^2 + 2as, s = \frac{1}{2}(u + v)t, s = ut + \frac{1}{2}at^2, s = vt - \frac{1}{2}at^2$

Key knowledge unit

Constant acceleration equations	2.1.2.3

Formulas for this lesson

Previous lessons		New formulas
8A	$v_{avg} = \frac{\Delta s}{\Delta t}$	$v = u + at$
8A	$a_{avg} = \frac{\Delta v}{\Delta t}$	$s = \frac{1}{2}(u + v)t$
		$s = ut + \frac{1}{2}at^2$
		$s = vt - \frac{1}{2}at^2$
		$v^2 = u^2 + 2as$

Constant acceleration equations 2.1.2.3

OVERVIEW

The five constant acceleration equations describe the motion of an object in terms of time, displacement, initial and final velocities, and acceleration. They can be used for both horizontal and vertical motion.

THEORY DETAILS

The constant acceleration equations, or kinematic equations, are a set of equations that allow us to mathematically describe motion. As the name suggests, they use the linear shape of velocity-time graphs under constant acceleration to model relationships between displacement, velocity, time and acceleration.

The equations will be expressed in terms of the following variables:

- s (m) – displacement from initial position (the change in position of an object)
- t (s) – the change in time (the difference between t_2 and t_1)
- a (m s^{-2}) – acceleration (the rate of change of velocity $a_{avg} = \frac{\Delta v}{\Delta t}$)
- u (m s^{-1}) – initial velocity (the velocity of the object at t_1)
- v (m s^{-1}) – final velocity (the velocity of the object at t_2)

USEFUL TIP

t really represents Δt, however in VCE Physics it is generally written in its abbreviated form for clarity and conciseness. In future, note that $t = t_2 - t_1$.

What are the constant acceleration equations?

Under constant acceleration, the graph of velocity against time will be linear, as in Figure 1. The gradient of the line is given by $\frac{\Delta v}{\Delta t} = a$. Since $\Delta v = v - u$, we can rewrite this equation as $\frac{v-u}{\Delta t} = a$. Rearranging this to make v the subject will result in the first constant acceleration equation.

$$v = u + at$$

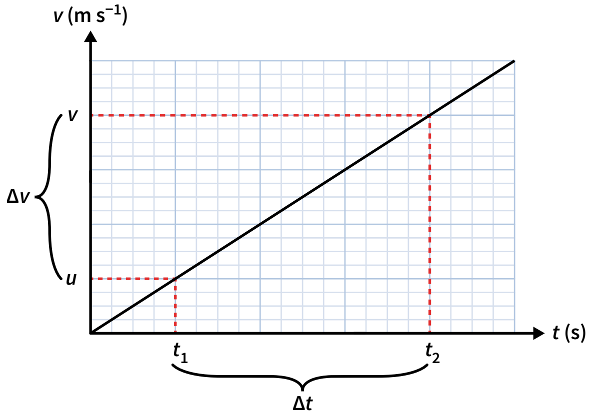


Figure 1 A velocity-time graph showing a change in velocity, $\Delta v = v - u$, that occurs over a time interval $\Delta t = t_2 - t_1$.

The second equation comes from calculating the area under this graph. From Lesson 8B, we know that the area from t_1 seconds to t_2 seconds is equal to the displacement of the object over that time period.

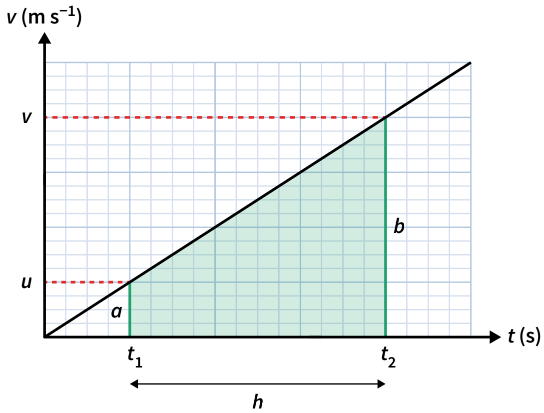


Figure 2 The green area under the velocity-time graph between t_1 and t_2 is equal to the displacement, s.

The area in Figure 2 is given by the formula for a trapezium, or $A = \frac{1}{2}(a + b)h$. This gives the second constant acceleration equation.

$$s = \frac{1}{2}(u + v)t$$

The area under the graph can also be represented as the sum of a rectangle and a triangle, as shown in Figure 3.

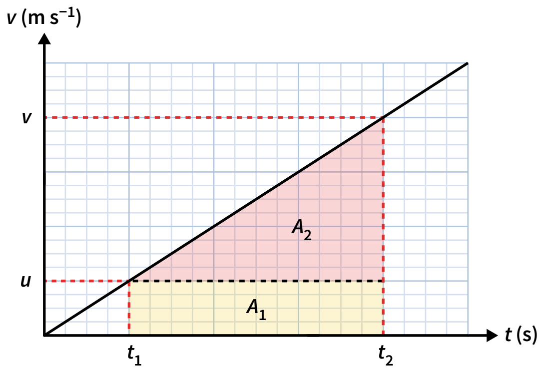


Figure 3 The same area from Figure 2 can be split into a rectangle (A_1) and a triangle (A_2).

The total area or displacement is equal to the sum of A_1 and A_2.

- A_1 is a rectangle with $Area = length \times width = u(t_2 - t_1) = ut$
- A_2 is a triangle with $Area = \frac{1}{2} \times base \times height = \frac{1}{2} \times (t_2 - t_1) \times (v - u)$
  - Recall from the first constant acceleration equation that $(v - u) = at$
  - Therefore $A_2 = \frac{1}{2} \times t \times at = \frac{1}{2}at^2$

Therefore the displacement, s, will be given by the third constant acceleration equation.

$$s = ut + \frac{1}{2}at^2$$

The same area we wish to calculate can also be expressed as the area of a large rectangle minus a smaller triangle.

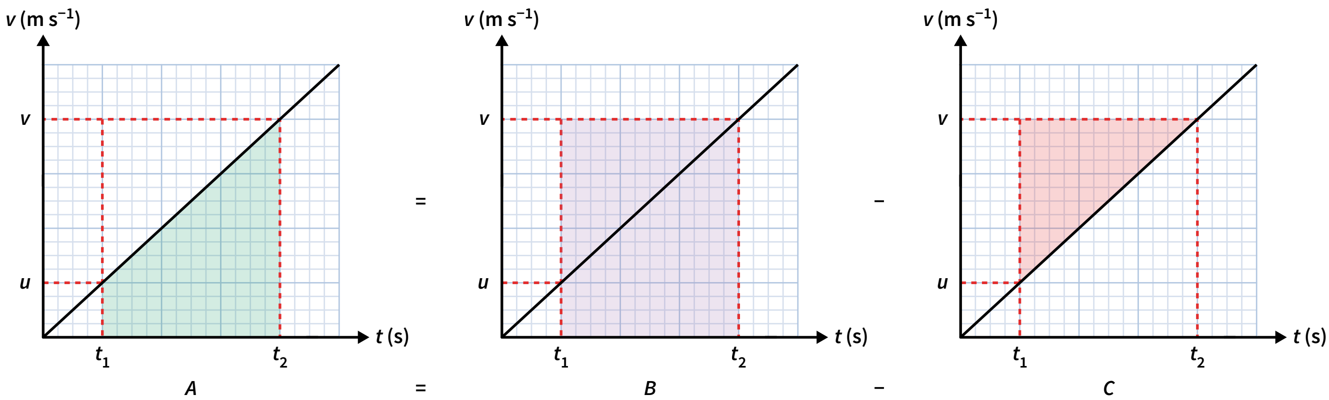


Figure 4 The green area (A) is equal to the purple area (B) minus the pink area (C).

In Figure 4, the purple area is given by $v \times t$. The pink triangle has an area equal to A_1 from Figure 3, of $\frac{1}{2}at^2$. Therefore, by subtracting C from B to produce A, we obtain the fourth constant acceleration equation.

$$s = vt + \frac{1}{2}at^2$$

Unlike the previous equations, the fifth and final equation will not contain t.

If $v = u + at$, then by squaring both sides of this equation we get $v^2 = u^2 + 2uat + a^2t^2$. The next step is to factor out a common factor of $2a$ from the last two terms on the right-hand side. So, $v^2 = u^2 + 2a\left(ut + \frac{1}{2}at^2\right)$. Recognise that the expression in the brackets is equal to the right-hand side of the third constant acceleration equation, $s = ut + \frac{1}{2}at^2$. By way of substitution, this leaves us with the final constant acceleration equation.

$$v^2 = u^2 + 2as$$

Some points to note about these equations are:

- They apply to both horizontal and vertical motion with **constant acceleration**.
- They apply to objects experiencing a constant net force, so variable forces like air resistance are generally ignored.

Acceleration due to gravity

Objects near the surface of the Earth accelerate downwards because of the force due to gravity. For vertical motion in VCE Physics, acceleration is given by $g = 9.8$ m s^{-2} downwards (or -9.8 m s^{-2} when upwards is defined as positive), unless otherwise specified. The force due to gravity will be covered in further detail in Lesson 9A.

Application

There are five variables we can be asked to calculate in motion problems:

- Each constant acceleration equation contains four of the five variables.
- If we are given three variables and wish to find a fourth, there will be at least one appropriate equation we can use.

This process of selecting the right equation is shown in Figure 5.

- Example 1 – *"A train leaves a station and accelerates at 5 m s^{-2}. How long does it take for the train to reach a speed of 100 m s^{-1} given that it starts from rest?"*
- Example 2 – *"A ball is thrown upwards with an initial velocity, such that it takes 5 seconds for the ball to return to the point it started at. Calculate this initial velocity."*

	Example 1	Example 2
What do we have? / What do we need?	s u v a t	s u v a t
	$v = u + at$	$v = u + at$
Circle the corresponding variables. If all are circled, we can use the equation.	$s = ut + \frac{1}{2}at^2$	$s = ut + \frac{1}{2}at^2$
	$s = vt - \frac{1}{2}at^2$	$s = vt - \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$	$v^2 = u^2 + 2as$
	$s = \frac{1}{2}(v+u)t$	$s = \frac{1}{2}(v+u)t$

Figure 5 Two examples of the process used to find the appropriate constant acceleration equation

It is important to remember that since displacement, velocity and acceleration are all vector quantities, they will all need to be acting in the same dimension, that is, either all of them vertically or all of them horizontally.

When performing calculations, it is also important to make sure that the units for different quantities are in SI units.

USEFUL TIP

In general, we define vectors pointing upwards or to the right to be positive and vectors downwards or to the left to be negative. However, it may be helpful in particular situations to do the opposite in order to make calculations more convenient by avoiding negative values. The most important thing is to be consistent with your choice.

Worked example 1

A car, starting from a stationary position, accelerates up to a speed of 30.0 m s^{-1} over a period of 10.0 seconds. How far does it travel from its starting position in this time?

Working	Process of thinking
	The initial velocity is zero since the car starts from rest. $u = 0$ m s^{-1}, $v = 30.0$ m s^{-1}, $t = 10.0$ s $s = ?$ m
$s = \frac{1}{2}(u+v)t$	Select the appropriate constant acceleration equation. s u v a t $v = u + at$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(u+v)t$
$s = \frac{1}{2}(0 + 30.0) \times 10.0 = \frac{1}{2} \times 30.0 \times 10.0 = 150$ m	Substitute in the given values and solve for displacement (s).
The car travelled 150 m over the 10 seconds.	Provide the answer within the context of the question.

Worked example 2

A ball is thrown straight up in the air at an initial speed of 24.5 m s^{-1}. Use this information to calculate the maximum height of the ball.

Working	**Process of thinking**
	$a = -9.8$ m s^{-2} since this is vertical motion.
	At the maximum height, the ball is momentarily stationary, so $v = 0$ m s^{-1}.
$v^2 = u^2 + 2as$	Select the appropriate constant acceleration equation. s u v a t $v = u + at$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(u+v)t$
$0^2 = 24.5^2 + 2 \times (-9.8) \times s$ $s = 30.6$ m	Substitute in the given values and solve for displacement (s).
The ball reached a maximum height of 30.6 m above its starting point.	Provide the answer within the context of the question.

The constant acceleration equations can also be used in scenarios where two objects are in motion at the same time. The time values used in both calculations must be the same.

Worked example 3

Car *A* drives past a stationary Car *B* at 15 m s^{-1}. Car *B* instantly begins to accelerate at 5.0 m s^{-2} until it has caught up to Car *A*. Calculate how long it takes for this to occur.

Working	**Process of thinking**
$v = \frac{s_A}{t}$	Car *A* travels at constant velocity so *displacement = velocity × time*.
$15 = \frac{s_A}{t} \therefore s_A = 15t$	$u = v = 15$ m s^{-1}, $a = 0$ m s^{-2}, $s = ?$ m
$s_B = ut + \frac{1}{2}at^2 = 0 \times t + \frac{1}{2} \times 5.0 \times t^2 = 2.5t^2$	Car *B* begins from rest so its initial velocity, u, is 0 m s^{-1}. $u = 0$ m s^{-1}, $a = 5.0$ m s^{-2}, $s = ?$ m
$s_A = s_B$ $15t = 2.5t^2$	When Car *B* catches up to Car *A*, their displacements will be the same. Substitute in both equations for t.
$15 = 2.5t$ $t = 6.0$ s	Solve for t.
It takes 6.0 s for Car *B* to catch up to Car *A*.	Provide the answer within the context of the question.

Theory summary

- Under constant acceleration (including $a = 0$) the motion of an object in one dimension can be described by the following equations:
  - $s = \frac{1}{2}(u + v)t$
  - $v = u + at$
  - $s = ut + \frac{1}{2}at^2$
  - $s = vt - \frac{1}{2}at^2$
  - $v^2 = u^2 + 2as$
- Each equation contains four of the five possible motion variables. To determine which equation to use:
  - identify the variables given in the question
  - identify the variable you are solving for
  - find the constant acceleration equation that contains the four variables (and **not** the fifth variable).
- For vertical motion in VCE Physics, acceleration is given by $g = 9.8\ \text{m s}^{-2}$ downwards (or $-9.8\ \text{m s}^{-2}$), unless otherwise specified.

USEFUL TIP

When using the constant acceleration equations which involve t^2 to find time, you may encounter a quadratic equation to solve. To avoid this, try using $v^2 = u^2 + 2as$ and then $v = u + at$ to solve for t instead. See the deconstructed exam-style question for an example.

KEEN TO INVESTIGATE?

YouTube video: BBC – Brian Cox visits the world's biggest vacuum
youtu.be/E43-CfukEgs

YouTube video: MrRyanPitcher – Free Fall and Terminal Velocity
youtu.be/vmeqV0WjGWM

CONCEPT DISCUSSION QUESTION

The Museum of Old and New Art (MONA) contains a water display (youtu.be/MepPl-4KjZ8) where water droplets fall in patterns to produce different words. We can model each of the water drops as an object falling with constant acceleration, g. Discuss how the appearance of a given word will change as it moves from the top of the display to the bottom.

Answers on page 507

Image: Willowtreehouse/Shutterstock.com

Hints

What is the relative velocity of a water drop at the top of the word compared to one at the bottom?

How does the velocity of a water drop change as it falls?

Under constant acceleration, what is the relationship between displacement and velocity?

8C Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following lists contains only correct constant acceleration equations?

A $u^2 = v^2 + 2as,\ s = \frac{\Delta v}{\Delta t},\ s = ut + \frac{1}{2}ta^2$

B $v = u + at,\ s = ut - \frac{1}{2}at^2,\ v = usa^2 + t$

C $s = \frac{1}{2}(u + v)t,\ v^2 = u^2 + 2as,\ s = ut + \frac{1}{2}at^2$

D $s = u + at,\ s = \frac{1}{2}(u + v)t,\ t = va + us^2$

Question 2

Match the appropriate constant acceleration equation to the situation where it is most applicable to use.

Kinematic equation

- $v^2 = u^2 + 2as$
- $s = vt - \frac{1}{2}at^2$
- $s = \frac{1}{2}(u + v)t$
- $v = u + at$

Situation

a The time a ball spends in the air if its final velocity is 20 m s^{-1} downwards and it lands where it started

b The displacement of a train as it goes from 50 m s^{-1} to 60 m s^{-1} in 5 seconds

c The acceleration of a car if it takes 100 metres for it to go from 25 m s^{-1} to a complete stop

d The final velocity of a cyclist if they begin from rest and accelerate at 4 m s^{-2} for 3 seconds

Question 3

For each of the following scenarios, determine whether or not enough information is provided to find the bolded variable. Ignore the effects of air resistance throughout.

a **Horizontal displacement** – a car approaching an intersection decelerates at a m s^{-2} for t seconds without coming to a stop.

b **Maximum height** – a ball is thrown upwards and takes t seconds to reach its peak.

c **Vertical acceleration** – a ball is thrown up with an initial velocity of u m s^{-1} and takes t seconds to reach its maximum height.

d **Final velocity** (just before landing) – a ball is thrown upwards at an initial velocity of u m s^{-1} and lands in the same place it started.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 4 (4 MARKS)

Jamieson is competing in his school's 3-metre diving competition. For his last dive, he is performing a forward somersault. The duration of the dive must be exactly 1.75 seconds or he will under- or over-rotate before hitting the water. He jumps vertically upwards off the board at 6.0 m s^{-1} and takes t seconds to land in the pool. Take up as positive.

Prompts

a What is his acceleration for the dive?

- **A** 9.8 m s^{-2}
- **B** −9.8 m s^{-2}
- **C** 6.0 m s^{-1}
- **D** More information is required to determine this.

b What is his displacement for the dive?

- **A** 3 m
- **B** 0 m
- **C** −3 m
- **D** More information is required to determine this.

c We can split the total time of the dive into the duration of upward motion (t_1) and downward motion (t_2). What is the value of t_1?

- **A** −0.61 s
- **B** 1.63 s
- **C** 0.61 s
- **D** 1.75 s

d What is Jamieson's change in displacement from $t = 0$ s to $t = t_1$ s?

- **A** −3 m
- **B** −1.8 m
- **C** 7.4 m
- **D** 1.8 m

e Which of the following correctly gives some of the known variables for the **downward motion of the dive only**?

- **A** $a = -9.8$ m s^{-2}, $u = 6.0$ m s^{-1}, $s = -3.0$ m
- **B** $a = -9.8$ m s^{-2}, $u = 0$ m s^{-1}, $s = -4.8$ m
- **C** $a = 9.8$ m s^{-2}, $u = 0$ m s^{-1}, $s = -3.0$ m s^{-1}
- **D** $a = 0$ m s^{-2}, $u = 6.0$ m s^{-1}, $s = -4.8$ m

f What is the value of his final velocity (i.e. the moment he hits the water)?

- **A** −9.7 m s^{-1}
- **B** 9.7 m s^{-1}
- **C** 6.0 m s^{-1}
- **D** 0 m s^{-1}

g What is the value of t_2?

- **A** 0.99 s
- **B** 1.75 s
- **C** 1.14 s
- **D** 1.0 s

Question

h Determine whether or not Jamieson performs the dive successfully. If not, determine whether he would over – or under-rotate. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 5 (2 MARKS)

Patricia, a drag-race enthusiast, is testing her new car down a straight road. Find the magnitude of her change in displacement if she starts from rest and finishes with a velocity of 45 m s^{-1} after 6.0 seconds.

Question 6 (2 MARKS)

A motorcyclist accelerates along a highway at a rate of 2.50 m s^{-2} for 10.0 seconds and finishes with a speed of 24.0 m s^{-1}. Calculate the distance the rider covers in this time.

Question 7 (3 MARKS)

Rico is throwing a ball up and down to herself. She tosses it up with an initial velocity of u m s^{-1}. The ball travels upwards, reaches its peak, and then falls back down again such that after 2.5 seconds, it has a velocity of 11 m s^{-1} downwards. Find u.

Question 8 (5 MARKS)

Pebbles is launching a water bomb attack out the window of her apartment onto a group of her unsuspecting friends 15 metres directly below her. One of the balloons hits her friends at a speed of 18 m s^{-1}. Pebbles claims that she did not throw the balloon out of the window, but instead dropped it after it slipped from her hands.

- **a** Use the information provided to calculate the magnitude of the initial velocity of the water balloon. (3 MARKS)
- **b** Hence explain whether or not Pebbles' claim is true. (2 MARKS)

Question 9 (3 MARKS)

Santush is trying his hand at lawn bowls. The green is 40 metres in length. For this question, we will assume that the ball decelerates at a constant rate of 0.35 m s^{-2} due to friction from the grass. To win the game, Santush must have the ball stop right at the edge of the green. If the ball is in motion for 18 seconds, determine whether or not he will win the game. Show your working.

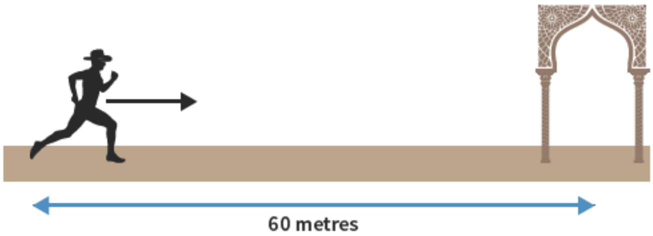
Question 10 (6 MARKS)

Mavis has stolen a painting from the nearby art gallery and is fleeing from the security on her motorbike at a constant speed of 54 km h^{-1}. On her way, she travels past a police officer in their car who takes 10 seconds to finish his doughnut and start the car before pursuing. He accelerates at 5 m s^{-2} for 4 seconds before maintaining a constant speed.

- **a** Calculate the time it takes for the police officer to catch Mavis. (5 MARKS)
- **b** Calculate how far away the police car is from his starting position when he catches her. (1 MARK)

Question 11 (4 MARKS)

Indiana Jones is in the depths of a Mayan temple searching for a priceless idol. He needs to make it down the 60 metre corridor and through the doorway to the treasure in 9.0 seconds before the floor on which he is running gives out and leaves him with no escape.



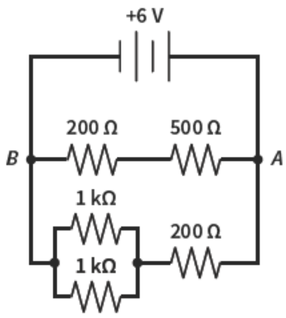
Images: msr melooo1, Michal Sanca, denisik11/Shutterstock.com

He starts from rest and accelerates at a m s^{-2} for 3.0 seconds after which point he maintains a constant speed. What is the minimum magnitude of a he can have if he is to make it through the doorway in time?

Previous lessons

Question 12 (3 MARKS)

Calculate the equivalent resistance between points A and B in the circuit below.



Question 13 (3 MARKS)

Describe the electrostatic force and the strong force and how they produce stable or radioactive nuclei.

Key science skills

Question 14 (7 MARKS)

A student is performing an experiment where she drops a ball from the second floor of her science building and uses speed gates placed at different heights to calculate the magnitude of the ball's velocity at given times. Some of the results are provided below.

Velocity (m s^{-1})	5	10.6	17	22	26
Time (s)	0.4	1.1	1.9	2.4	3.0

- **a** Sketch the graph of velocity against time, making sure to include a line of best fit. (3 MARKS)
- **b** Calculate the gradient of this line and discuss what it represents in this question. (2 MARKS)
- **c** Give one reason why the value of the gradient calculated in **b** is different from the value we would expect. (2 MARKS)

CHAPTER 8 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Use the following information to answer Questions 1 and 2.

A man is standing on the edge of a 30 m tall bridge and throws a tennis ball vertically upwards with a speed of 15 m s^{-1}. Take the acceleration due to gravity, g, to be 9.8 m s^{-2}. Ignore the effects of air resistance.

Question 1

Which of the following is closest to the maximum height of the tennis ball above the ground?

A 11 m

B 30 m

C 41 m

D 74 m

Question 2

After reaching its maximum height, what is the speed of the tennis ball when it returns to the height it was thrown from?

A 0 m s^{-1}

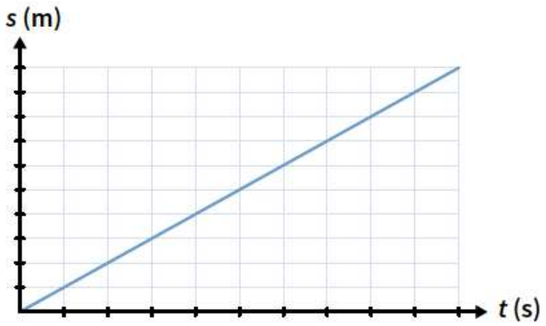
B 8 m s^{-1}

C 15 m s^{-1}

D 16 m s^{-1}

Question 3

The provided displacement-time graph represents the motion of a toy car over a period of time.

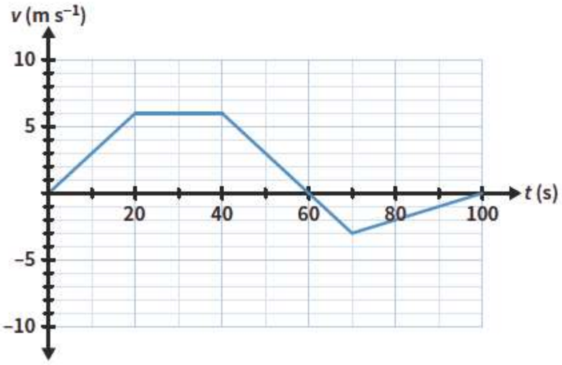


Which of the following options correctly describes the velocity and acceleration of the toy car?

	Velocity	Acceleration
A	Constant	Increasing
B	Constant	Zero
C	Increasing	Increasing
D	Increasing	Constant

Use the following information to answer Questions 4 and 5.

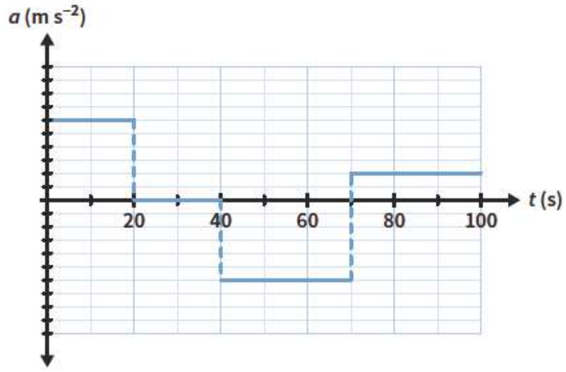
The provided velocity-time graph represents the motion of a runner along a straight track.



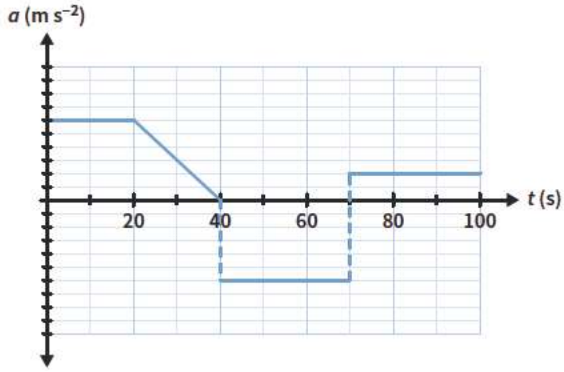
Question 4

Which of the following acceleration-time graphs best represents the motion of the runner?

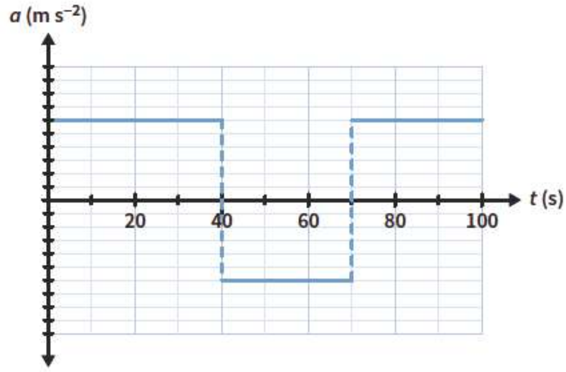
A



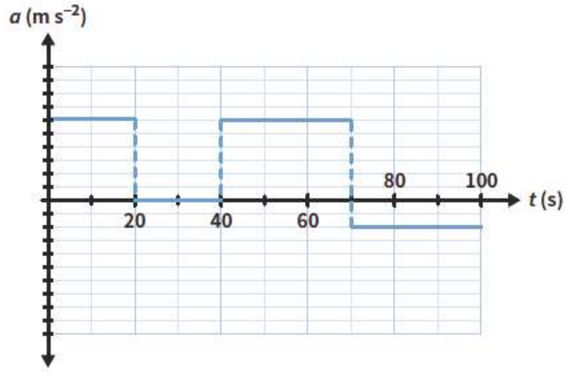
B



C



D



Question 5

Using the velocity-time graph, which of the following best represents the magnitude of the displacement of the runner after 100 seconds?

A 60 m

B 180 m

C 240 m

D 300 m

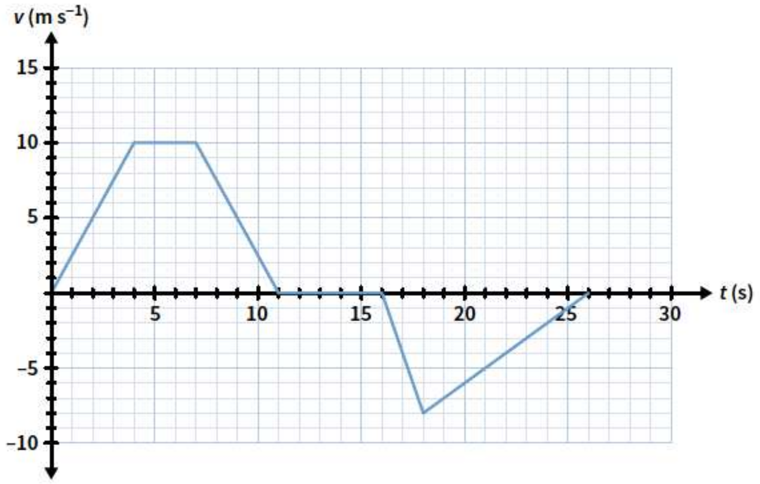
SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (7 MARKS)

The provided graph shows how the velocity of a cyclist varied as they travelled along a straight stretch of road, where west is the positive direction on the *y*-axis.



a Determine the magnitude and direction of the acceleration of the cyclist 9 seconds after they began riding. (2 MARKS)

b Calculate the distance travelled by the cyclist over the 26-second journey. (2 MARKS)

c Find the magnitude and direction of the cyclist's final displacement from their starting position. (2 MARKS)

d Determine the magnitude and direction of the average velocity of the cyclist over their journey. (1 MARK)

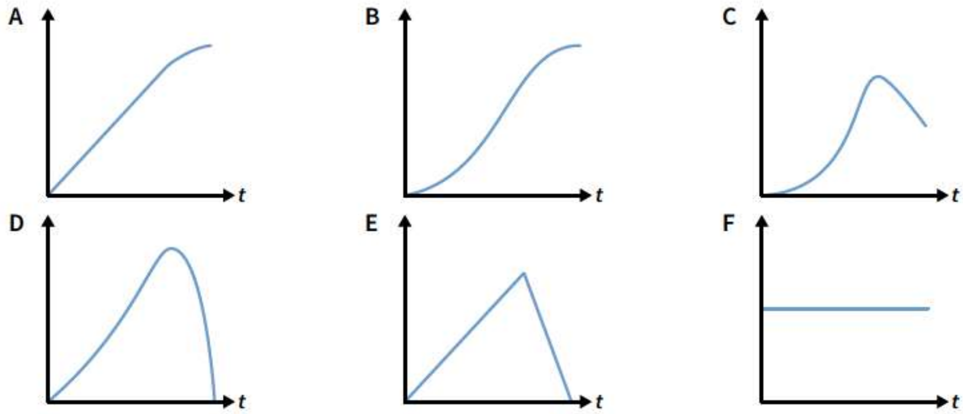
Question 7 (7 MARKS)

Whilst driving to school, a student who is late for their physics exam accelerates their car from rest over a distance of 300 m in 14.0 seconds. The student then sees a stop sign and applies the brakes, stopping the car in 7.5 seconds. Assume that both the acceleration and deceleration of the car are constant.

a Determine the magnitude of the acceleration of the car over the first 300 m. (2 MARKS)

b Calculate the average speed of the car during the whole accelerating and decelerating period. (3 MARKS)

The provided graphs (A–F) show time on the horizontal axis and velocity or distance on the vertical axis.



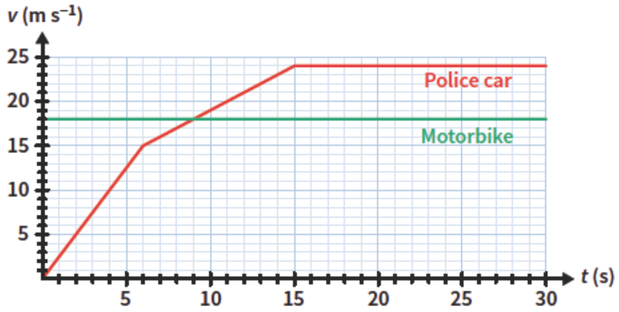
c Which of the provided graphs (A–F) best represents the distance-time graph of the car during the accelerating and decelerating periods? (1 MARK)

d Which of the provided graphs (A–F) best represents the velocity-time graph of the car during the accelerating and decelerating periods? (1 MARK)

Adapted from 2002 VCAA Exam 2 Area 1 Q1–4

Question 8 (6 MARKS)

A motorbike speeds through a school zone at 18 m s^{-1} and passes a stationary police car at t = 0 seconds. The police car accelerates and attempts to catch up with the motorbike. The provided graph shows how the velocities of the police car and motorbike vary over time.



a Determine the magnitude of the average acceleration of the police car over the first 10 seconds. (1 MARK)

b Which of the following options correctly identifies how the velocity and acceleration of the police car change from just before t = 6 seconds to just after t = 6 seconds? (1 MARK)

A Velocity increases, acceleration increases

B Velocity increases, acceleration decreases

C Velocity decreases, acceleration increases

D Velocity decreases, acceleration decreases

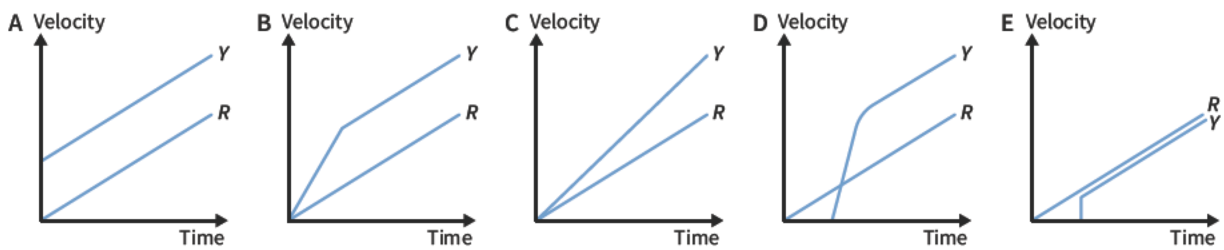
c Determine the time it takes for the police car to catch the motorbike from the time t = 0 s. (4 MARKS)

Question 9 (5 MARKS)

Two friends are at the top of an apartment building dropping water balloons on people who walk past. One friend drops a red water balloon from rest and 0.50 seconds later the other friend throws a yellow water balloon vertically downwards at 2.0 m s^{-1}. The apartment building is 20 m high. Take the acceleration due to gravity, g, to be 9.8 m s^{-2}. Ignore the effects of air resistance.

a Determine which water balloon hits the ground first. (4 MARKS)

b Which of the following velocity-time graphs (A–E) best represents the motion of the red water balloon (R) and the yellow water balloon (Y)? (1 MARK)



UNIT 2 AOS 1, CHAPTER 9

Forces and motion

09

Key knowledge

- model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body, $F_g = mg$, where g is the gravitational field strength (9.8 N kg^{-1} near the surface of Earth)
- model forces as vectors acting at the point of application (with magnitude and direction), labelling these forces using the convention 'force on A by B' or $F_{on\,A\,by\,B} = -F_{on\,B\,by\,A}$
- apply Newton's three laws of motion to a body on which forces act: $a = \frac{F_{net}}{m}$, $F_{on\,A\,by\,B} = -F_{on\,B\,by\,A}$
- apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and reaction forces
- calculate torque: $\tau = r_{\perp}F$
- investigate and analyse theoretically and practically translational forces and torques in simple structures that are in rotational equilibrium.

9A FORCES

When we want to get something moving, we apply a force. But how do we quantify these forces and how can we measure their effect? This lesson will introduce force vectors in one dimension, Newton's laws of motion, the gravitational force, and the normal force.

9A Forces	9B Force vectors in two dimensions	9C Inclined planes and connected bodies	9D Torque	9E Equilibrium

Study design dot points

- model forces as vectors acting at the point of application (with magnitude and direction), labelling these forces using the convention 'force on A by B' or $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$
- model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body, $F_g = mg$, where g is the gravitational field strength (9.8 N kg^{-1} near the surface of Earth)
- apply Newton's three laws of motion to a body on which forces act: $a = \frac{F_{net}}{m}$, $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$

Key knowledge units

Representing forces	2.1.7.1
The net force	2.1.7.2
Newton's first law	2.1.8.1
Newton's second law	2.1.8.2
Newton's third law	2.1.8.3
Force due to gravity	2.1.6.1
The normal force	2.1.7.3

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$F_{net} = ma$ Newton's second law
	$F_g = mg$ force due to gravity

Definitions for this lesson

force a push or a pull with an associated magnitude and direction (vector quantity)

gravitational force the force experienced by an object due to the gravitational field of another object

net force the vector sum of all forces acting on an object

Newton's first law law that states an object will accelerate only if a non-zero net force (unbalanced force) acts upon it

Newton's second law law that states the acceleration of an object is equal to the net force applied divided by the mass of the object being accelerated

Newton's third law law that states that for every force there is a reaction force of equal magnitude and opposite direction

normal force the contact force that acts between two objects with equal magnitude on each object and at right angles to the contact surfaces

Representing forces 2.1.7.1

OVERVIEW

A force is a push or a pull that has an associated magnitude and direction. Forces are responsible for causing changes in motion.

THEORY DETAILS

We are familiar with the idea of a force since we often exert forces ourselves. In physics, a force, F, is a push or a pull that by itself would cause a change in motion.

- Forces are vector quantities, having both magnitude and direction.
- Force magnitude is measured in newtons (N).
- We draw forces as arrows which point in the direction that the force is acting. A force arrow should begin at the point where the force is acting. The relative length of the arrow indicates the magnitude of the force.

For forces in one dimension their directions can be given as either a direction along a line, such as left and right, up and down, north and south, or positive and negative.

- The positive direction is often defined as upwards or to the right, however this can change depending on what is convenient for the question.
- The definition of which direction is positive should be explicitly stated.
- When we write force equations for one dimension, a force's direction can either be positive or negative.

Figure 1 Force vectors with magnitude F in the negative (left) and positive (right) directions. Since these arrows have the same length, the forces have the same magnitude.

Force diagrams

A force diagram is a representation of all the forces acting on an object. They help us visualise the directions and relative sizes of forces so that we can correctly analyse the effect of these forces on the object.

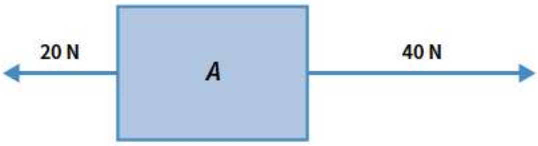


Figure 2 A force diagram showing the two forces acting on an object A

The net force 2.1.7.2

OVERVIEW

The net force acting on an object is the vector sum of all forces acting on that object.

THEORY DETAILS

The resultant force found by adding all the forces acting upon an object is the net force. The net force is often denoted as $F_{net} = \Sigma F$.

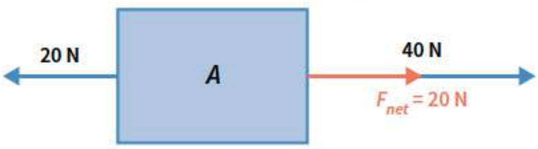
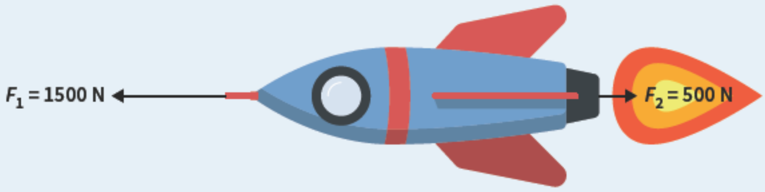


Figure 3 The net force on object A is the sum of all the forces acting upon the object.

To calculate the net force in one dimension, simply add each force, making sure to include the positive or negative sign to indicate direction.

Worked example 1

Calculate magnitude and direction of the net force acting on the rocket.



Working

Define left as the positive direction.

$F_{net} = 1500 + (-500) = 1000$ N

$F_{net} = 1000$ N to the left

Process of thinking

Since the rocket seems to be moving left, it is reasonable to define left as positive.

$F_1 = 1500$ N, $F_2 = -500$ N

To calculate the net force, add the left and right forces.

In the final answer, include the magnitude and direction.

Newton's first law 2.1.8.1

OVERVIEW

Newton's first law is: **an object will accelerate only if a non-zero net force acts upon it.**

THEORY DETAILS

Newton's first law states that an object will accelerate only if there is a non-zero net force acting upon it. If the net force acting on an object is zero, it will either remain at rest or keep moving at a constant velocity. This is known as being in translational equilibrium. An important conclusion of the law is that an object **can be moving even if there is no force applied.**

Newton's second law 2.1.8.2

OVERVIEW

Newton's second law is: **the acceleration of an object is equal to the net force applied divided by the mass of the object.**

THEORY DETAILS

Newton's second law states that the acceleration of an object is equal to the net force applied divided by the mass of the object. This gives the equation:

$$a = \frac{F_{net}}{m}$$

This equation is usually rearranged into the formula:

> $$F_{net} = ma$$
> F_{net} = net force (N), m = mass (kg), a = acceleration (m s^{-2})

Worked example 2

Determine the magnitude of acceleration of a 3000 kg truck when a net force with a magnitude of 1500 N is applied.

Working

$F_{net} = ma \quad \therefore 1500 = 3000 \times a$

$a = 0.5000$ m s^{-2}

Process of thinking

Use Newton's second law to relate force, mass, and acceleration: $F_{net} = 1500$ N, $m = 3000$ kg

Newton's third law 2.1.8.3

OVERVIEW

Newton's third law is: for every action force, there is a reaction force of equal magnitude and opposite direction.

THEORY DETAILS

Newton's third law states that for every force applied to an object, the object will apply a reaction force of equal magnitude and opposite direction on the object applying the action force.

For example, a rocket in the vacuum of space expels gases from its engine to accelerate. The rocket exerts a force to accelerate the gases backwards, causing the gases to exert a force of equal magnitude and opposite direction (forwards) on the rocket.

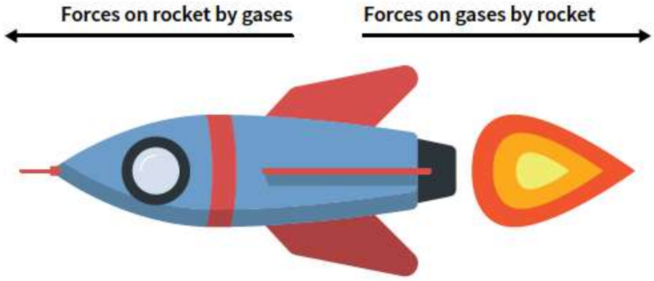


Figure 4 The action and reaction forces that cause a rocket to accelerate in space

> **USEFUL TIP**
>
> Note that the designation of a force being 'action' or a 'reaction' is arbitrary since one does not lead the other. The forces are an action-reaction pair.

For a pair of equal magnitude forces on bodies A and B to be an action-reaction pair, one force must be exerted on *A* by *B* ($F_{on\ A\ by\ B}$), with the other force exerted on *B* by *A* ($F_{on\ B\ by\ A}$). Additionally, since the reaction force is in an opposite direction, $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$.

Another example of Newton's third law is the striking of a football. When a foot strikes the ball, it exerts a force on the ball, $F_{on\ ball\ by\ foot}$, and the ball exerts an equal and opposite force on the foot, $F_{on\ foot\ by\ ball}$. However, since the mass of the ball is much smaller than the combined mass of the foot and the leg/person it is attached to, the magnitude of acceleration of the ball is much greater than the magnitude of acceleration of the foot.

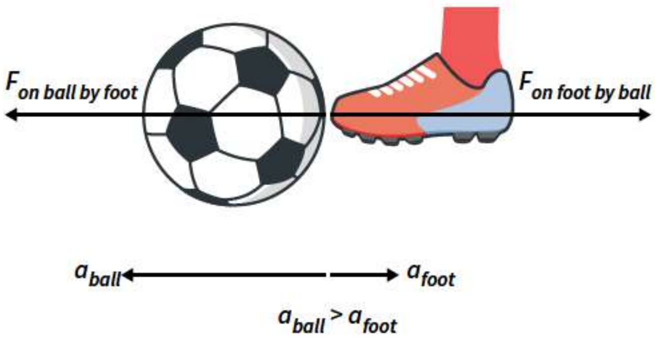


Figure 5 When a ball is kicked, it exerts an equal and opposite force on the foot, but the acceleration of the ball is greater than the acceleration of the foot since it has a smaller mass than that of the leg that the foot is attached to.

Force due to gravity 2.1.6.1

OVERVIEW

The force due to gravity experienced by an object is given by $F_g = mg$, where g is the gravitational field strength or acceleration due to gravity.

THEORY DETAILS

The force due to gravity attracts masses towards each other.

- A gravitational field has a gravitational field strength *g* which gives the force due to gravity per kg. The units of *g* are N kg^{-1}.
- This quantity *g* is also called the acceleration due to gravity because it is the acceleration when no other forces are acting. This means that equivalent units for *g* are m s^{-2}.
- At the Earth's surface, the gravitational field strength is taken to be 9.8 N kg^{-1} (m s^{-2}).

We use g to determine the force due to gravity using the equation:

> $F_g = mg$
>
> **F_g = force due to gravity (N), m = mass (kg), g = gravitational field strength/acceleration due to gravity (N kg^{-1} or m s^{-2})**

The vector for the force due to gravity is drawn acting from the centre of an object as it is a non-contact (field) force.

The reaction force for the gravitational force on a mass M_1 by another mass M_2 is the gravitational force on M_2 by M_1. A skydiver experiencing a gravitational force towards Earth is exerting an equal and opposite gravitational force on the Earth. However, because the mass of the Earth is so large, the acceleration from this force is negligible.

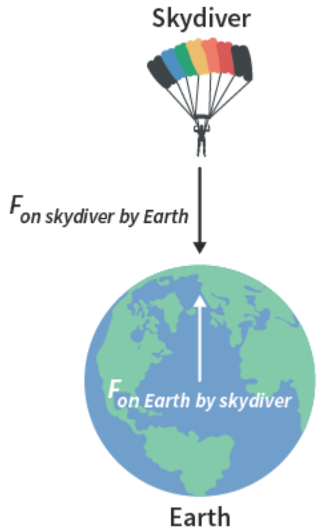


Figure 6 The gravitational action and reaction forces between a skydiver and the earth. The acceleration of the earth is negligible due to its large mass.

The normal force 2.1.7.3

OVERVIEW

The contact force that acts between two surfaces is known as the normal force. It always acts perpendicular to the plane of contact between the surfaces.

THEORY DETAILS

When an object A is in contact with another object B, they exert equal and opposite contact forces on each other, $F_{on\ B\ by\ A}$ and $F_{on\ A\ by\ B}$. We call this type of contact force the normal force, F_N. The normal force always acts perpendicular to the plane of contact between the surfaces.

- For an object that is not accelerating, the normal force ensures that the net force on object A is zero and so remains in translational equilibrium.
- If both objects are in free fall (accelerating due to gravity only) the normal force is zero.

Note that the gravitational force on an object and the normal force on an object are **not an action-reaction pair**. Since both forces are acting **on** the same object, these forces cannot be an action-reaction pair. The action-reaction pair is the two normal (or contact) forces.

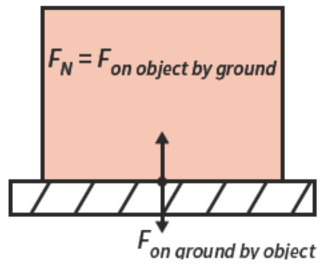
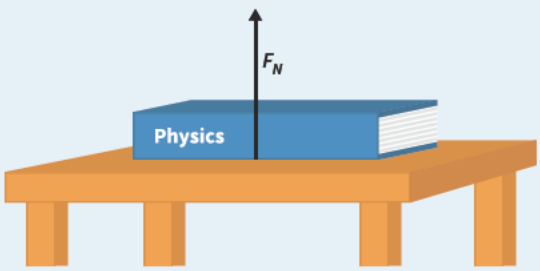


Figure 7 The normal force acting on an object sitting on the ground

Worked example 3

Determine the normal force exerted on a 3.0 kg book resting on a table. Assume that both the book and the table are in translational equilibrium. Take the gravitational field strength to be 9.8 N kg^{-1}.



Working	Process of thinking
Define the positive direction as upward.	Define the positive direction.
$F_{net} = (-F_g) + F_N = 0$	The net force on the book will be zero, since it is not accelerating. The forces acting on the book are the force due to gravity (which is negative since it acts downwards) and the normal force.
$\therefore F_N = -(-F_g)$ $F_N = mg = 3.0 \times 9.8 = 29.4$ N	The normal force will be equal and opposite to the gravitational force: m = 3.0 kg, g = 9.8 N kg^{-1}
F_N = 29 N upward	Include a magnitude and direction in the final answer.

Theory summary

- A force is a push or pull applied by one object on another.
  - Forces are vectors.
  - Force magnitude is measured in newtons (N).
- We draw forces as arrows pointing in the direction they act, with a length proportional to their magnitude, beginning at the point of application.
- Force diagrams show all of the forces acting on an object.
- The vector sum of all forces acting on an object is called the net force.
- Newton's laws:
  - 1st: An object will not accelerate unless a non-zero net force is applied.
  - 2nd: $F_{net} = ma$
  - 3rd: Every action force has an equal and opposite reaction force.
- The force due to gravity attracts all masses.
  - $F_g = mg$ where g is the gravitational field strength.
  - $g = 9.8\ \text{N kg}^{-1}$ near the surface of the Earth.
- The normal force F_N is the contact force that pushes objects away from each other in a direction that is perpendicular to the contact surfaces.

KEEN TO INVESTIGATE?

PhET 'Forces and Motion: Basics' simulation
phet.colorado.edu/en/simulation/forces-and-motion-basics

YouTube video: Crash Course Physics – Newton's Laws
youtu.be/kKKM8Y-u7ds

CONCEPT DISCUSSION QUESTION

A key conclusion of Newton's 1st law is that an object can be moving without any net force acting on it. With reference to this conclusion, discuss the magnitudes and directions of the horizontal forces that a car must exert on the road when the car is accelerating and when the car has a constant velocity.

Answers on page 507

Hints

What causes an object to accelerate?

What is needed for a car to maintain a constant velocity?

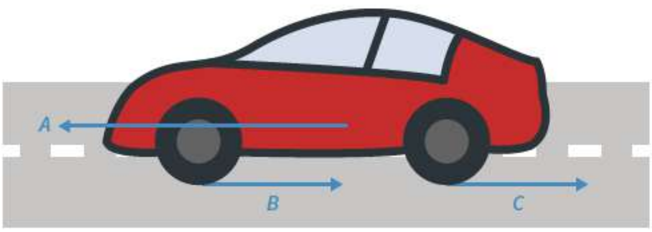
How do the forces that the car exerts on the road relate to the motion of the car?

9A Questions

THEORY REVIEW QUESTIONS

Question 1

Define a positive direction for forces in the following scenario and state whether forces *A*, *B*, and *C* act in a positive or negative direction.



Question 2

Select which of the following statements about a force is correct.

A A force is a property of an object due to its motion.

B A force must be present for an object to move.

C A force is an action that can have an effect on the motion of a body.

D A force is the energy of a body.

Question 3

Fill in the blanks to best complete the sentence.

When located in the Earth's __________ (atmosphere/gravitational field), bodies with __________ (solid centres/mass) experience a(n) __________(attractive/repulsive) force towards the Earth due to __________ (gravity/contact with other objects).

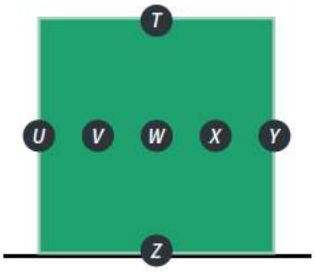
Use the following information to answer Questions 4 and 5.

Two friends are exerting forces on a 5 kg block.

- Demi is exerting a 200 N force to the right acting on the right face of the block.
- Sharni is exerting a 100 N force to the left acting on the left face of the block.
- A force due to gravity and a normal force are acting on the block.

Question 4

At which of the points labelled (*T*–*Z*) should the force arrows for Demi's force, Sharni's force, the force due to gravity, and the normal force begin?



Question 5

How should the length of the force arrows for Sharni's and Demi's forces compare?

A The arrow for Sharni's force should be longer than the arrow for Demi's force.

B The arrow for Sharni's force should be shorter than the arrow for Demi's force.

C The arrows should have equal length.

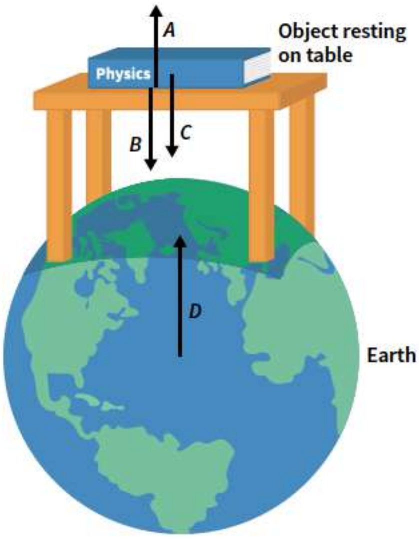
Question 6

Which row correctly defines Newton's three laws?

	Newton's 1st law	Newton's 2nd law	Newton's 3rd law
A	An object will only accelerate if a non-zero net force acts upon it.	For every action force, there is a reaction force of equal magnitude and opposite direction.	The acceleration of an object is equal to the net force applied divided by the mass of the object.
B	An object will only accelerate if a non-zero net force acts upon it.	The acceleration of an object is equal to the net force applied divided by the mass of the object.	For every action force, there is a reaction force of equal magnitude and opposite direction.
C	An object will be at rest if no net force acts upon it.	The acceleration of an object is equal to the net force applied divided by the mass of the object.	For every action force, there is a reaction force of equal magnitude and opposite direction.
D	An object will only accelerate if a non-zero net force acts upon it.	The acceleration of an object is equal to the net force applied multiplied by the mass of the object.	For every action force, there is a reaction force of equal magnitude and direction.

Question 7

Complete the included table to correctly label the diagram.



Force due to gravity on object by Earth	
Force due to gravity on Earth by object	
Normal force on table by object	
Normal force on object by table	

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (4 MARKS)

Four friends are exerting forces on a 5.0 kg rope in a 'tug-of-war'. The magnitude of the four forces are shown. Take the positive direction as to the right.

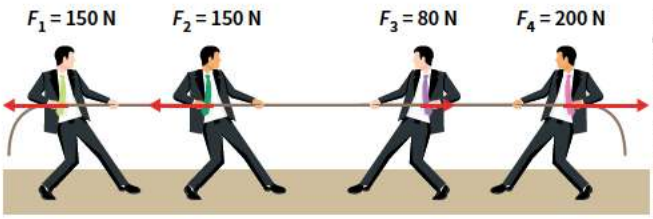


Image: hvostik/Shutterstock.com

Prompts

a Which option correctly states the sign that should be assigned to each force for calculations?

	F_1	F_2	F_3	F_4
A	negative	positive	positive	positive
B	positive	positive	positive	negative
C	negative	negative	positive	positive
D	positive	positive	negative	negative

b Which of the following is a correct equation for the net force acting on the rope? Remember to take the positive direction as to the right.

A $F_{net} = F_1 + F_2 - F_3 - F_4$

B $F_{net} = F_1 + F_3 - F_2 - F_4$

C $F_{net} = F_1 + F_2 + F_3 - F_4$

D $F_{net} = F_3 + F_4 - F_1 - F_2$

Question

c Determine the acceleration of the rope. (4 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (1 MARK)

Determine the magnitude of the force due to gravity acting on a 75.0 kg mass on the Earth's surface.

Question 10 (1 MARK)

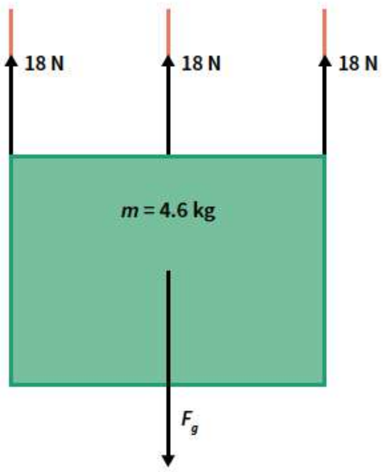
Determine the magnitude of the acceleration of a 20 kg toy car if its wheels exert a 120 N net force on the car.

Question 11 (1 MARK)

Determine the magnitude of the net force acting on a 60.0 kg skydiver if they are accelerating towards the Earth's surface at 7.60 m s^{-2}.

Question 12 (5 MARKS)

a Calculate the magnitude of the acceleration of the hanging mass shown in the diagram. Assume that the mass is near the surface of the Earth. (3 MARKS)



b Draw the net force acting on the mass. (2 MARKS)

Question 13 (6 MARKS)

A 30 kg box is sitting on a table near the Earth's surface.

a Calculate the magnitude of the normal force acting on the box if it is at rest. (2 MARKS)

b Calculate the magnitude of the normal force acting on the box if it and the table are accelerating towards the Earth at 9.8 m s^{-2}. (2 MARKS)

c Calculate the magnitude of the normal force acting on the box if it and the table are accelerating upwards at 2.0 m s^{-2}. (2 MARKS)

Question 14 (3 MARKS)

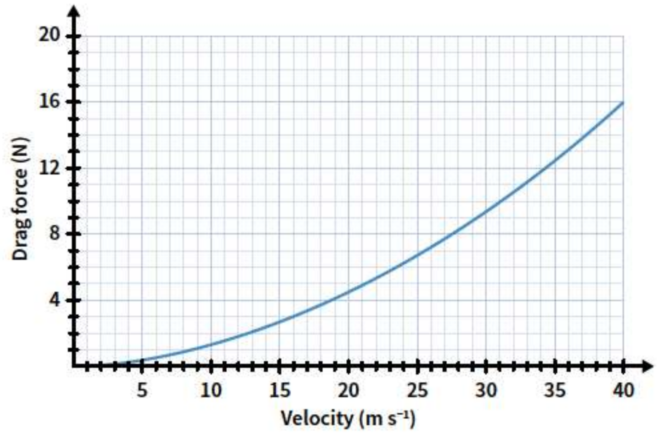
Explain, with reference to Newton's 3rd law, why the normal force acting on a ball that is at rest on the ground and the force due to gravity acting on the ball are not an action–reaction pair.

Question 15 (2 MARKS)

A spacesuit ejects small streams of air to move around. Explain how ejecting a stream of air can accelerate a spacesuit.

Question 16 (3 MARKS)

When a 1.5 kg object falls downwards towards the Earth, it experiences an aerodynamic drag force upwards.
The magnitude of the drag force is dependent on velocity, as shown in the force vs velocity graph.



Estimate the maximum speed (the speed reached when acceleration is zero, called terminal velocity) that the object will reach as it falls towards the Earth. Assume that $g = 9.8$ m s^{-2} and that the object falls from a high altitude. Justify your answer with reference to Newton's 1st or 2nd law.

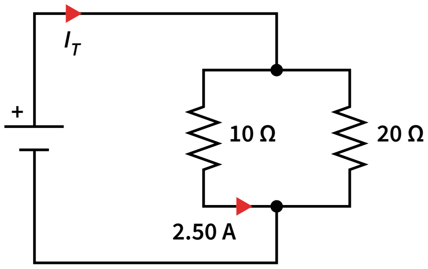
Question 17 (4 MARKS)

Determine the force F needed to accelerate this 18 kg wheelie bin at 2.0 m s^{-2} to the right given that there is a force of 12 N resisting its motion.

Previous lessons

Question 18 (3 MARKS)

Determine the total current passing through the voltage source in this parallel circuit.



Question 19 (3 MARKS)

A cyclist completes three complete loops of a velodrome in 2 minutes. The circumference of the velodrome is 350.0 m.

a What is the distance travelled by the cyclist? (1 MARK)

b What is the displacement of the cyclist? (1 MARK)

c What is the average velocity of the cyclist? (1 MARK)

Key science skills

Question 20 (7 MARKS)

Nu Tan collects data from an experiment on the bite force of different animals. The mass of each animal is recorded very precisely, but the bite force data has a measurement uncertainty of ±10 N.

Animal mass (kg)	Bite force (N)
4.0	30
6.0	50
22.0	180
45.0	355
85.0	680

a Plot the data on an appropriate graph. Include a line of best fit and uncertainty bars. (5 MARKS)

b Describe the relationship between animal mass and bite force. (2 MARKS)

9B FORCE VECTORS IN TWO DIMENSIONS

Having learned about types of forces and Newton's laws in Lesson 9A, this lesson will expand our understanding to include force vectors in two dimensions and how to add and subtract these vectors. This knowledge will later be used to analyse more complex force systems.

9A Forces	9B Force vectors in two dimensions	9C Inclined planes and connected bodies	9D Torque	9E Equilibrium

Study design dot point

- apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and reaction forces

Key knowledge units

Force vector components	2.1.9.1
Addition and subtraction of forces in two dimensions	2.1.9.2

No previous or new formulas for this lesson

Force vector components 2.1.9.1

OVERVIEW

A single vector can be resolved into two perpendicular components using trigonometry.

THEORY DETAILS

In Lesson 9A we learned about force vectors and how to add and subtract them in one dimension. We often need to deal with forces that act at an angle in a two-dimensional plane; examples of two-dimensional planes include an *x-y* (horizontal-vertical) plane, or a plane that uses compass directions as shown in Figure 1.

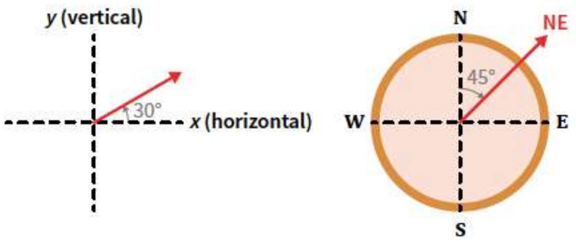


Figure 1 The direction of a force in a two-dimensional plane, such as the *x-y* plane or a compass plane, can be described by its angle measured from a reference direction.

In these situations, the vectors can be resolved (broken down) into two perpendicular components, which are equivalent to the original vector. For example, a force that acts up and to the right as in Figure 2 will have a component to the right and another component upwards.

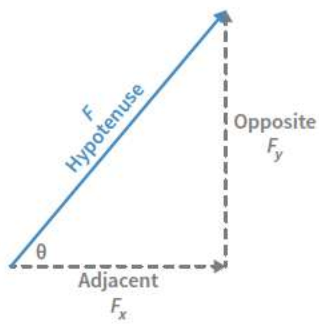


Figure 2 A force vector in a 2D plane is equivalent to two perpendicular components.

Trigonometry is used to determine the magnitude of the two perpendicular components. When the angle, θ, is measured from the *x*-direction:

$$F_x = F\cos(\theta)$$

$$F_y = F\sin(\theta)$$

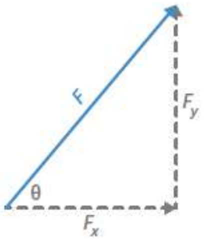
Pythagoras' theorem and trigonometry are used for the reverse process: to determine the magnitude and direction of a force from its perpendicular components.

To find the magnitude, F:

$$F = \sqrt{F_x^{\,2} + F_y^{\,2}}$$

To find the angle, θ:

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$



$$F = \sqrt{F_x^2 + F_y^2}$$

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

$$F_x = F\cos(\theta)$$

$$F_y = F\sin(\theta)$$

Figure 3 Equations relating the magnitude, F, and angle, θ, of a force vector with its components in the x-y plane

We can visualise vector components as shadows of the original vector. As we see in Figure 4(a), if the Sun were to shine down from directly above the vector, the shadow would represent the horizontal component, F_x. If the Sun were to shine horizontally from the side of the vector, as in Figure 4(b), the shadow would represent the vertical component, F_y.

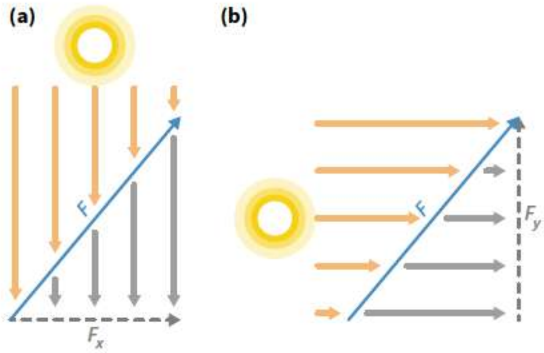
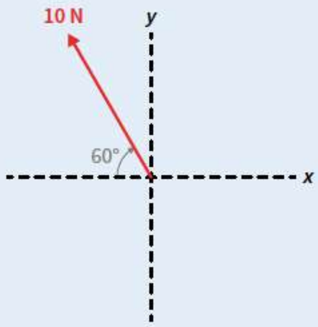


Figure 4 **(a)** The horizontal component, F_x, and **(b)** the vertical component, F_y, of a force in two dimensions can be visualised as the shadows of that vector.

Worked example 1

A force of 10 N acts at 60° above the negative direction of the x-axis. Determine the components of this force in the x- and y-directions. Take the positive directions as to the right and upwards.



Working	Process of thinking
$F_x = F\cos(\theta)$	The x-component is the adjacent side so we use the equation $F_x = F\cos(\theta)$.
$F_x = -10 \times \cos(60°) = -5.0$ N	$F = 10$ N, $\theta = 60°$ As left is negative, F_x will be negative.
$F_y = F\sin(\theta)$	The y-component is the opposite side so we use the equation $F_y = F\sin(\theta)$.
$F_y = 10 \times \sin(60°) = 8.7$ N	As up is positive, F_y will be positive.

Addition and subtraction of forces in two dimensions 2.1.9.2

OVERVIEW

Forces can be added or subtracted graphically using the tip-to-tail method, or geometrically by considering the components of forces.

THEORY DETAILS

When multiple forces act on an object, the net force is the vector sum of the various forces. There are two approaches we can use to add or subtract force vectors:

- Approach 1: graphically adding and subtracting vectors
- Approach 2: geometrically adding and subtracting vectors

Graphically adding and subtracting vectors

To graphically add two forces, connect the tip of the first vector to the tail of the second vector. The resultant force will be the line between the tail of the first vector and the tip of the second.

Consider the force vectors A and B shown in Figure 6. The tip of the first vector, A, is connected to the tail of the second vector, B, and the resultant vector, C, is from the tail of A to the tip of B. This principle applies to the addition of any number of vectors.

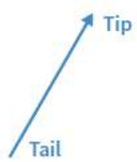


Figure 5 The tip and tail of a vector

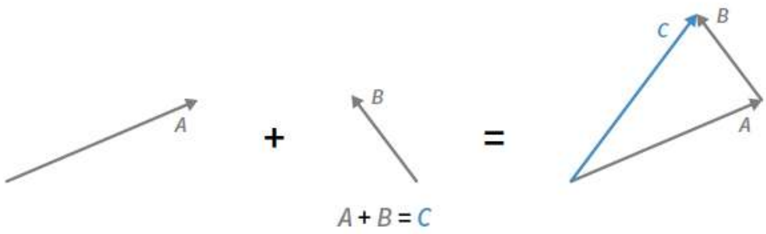


Figure 6 The graphical addition of vectors *A* and *B* being equal to vector *C*

To graphically subtract vectors, such as *A* − *B*, we take the negative of the vector being subtracted and treat the operation as an addition: *A* + (−*B*). The negative of a vector will simply have the same magnitude and the opposite direction, meaning the tip and tail will swap. This is shown in Figure 7.

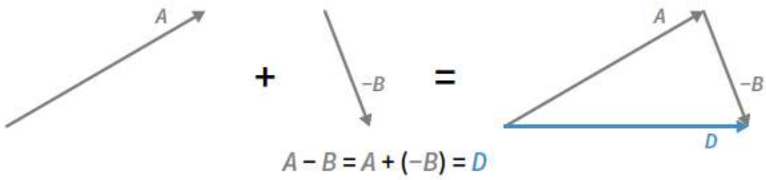


Figure 7 The graphical subtraction of vector *B* from vector *A* being equal to vector *D*

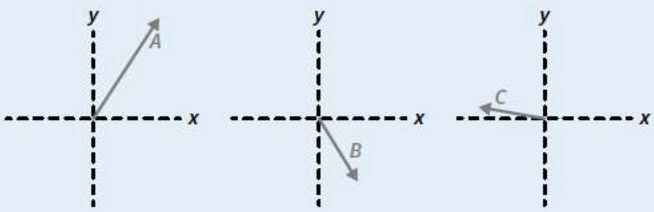
Worked example 2

Graphically represent the following vector additions and subtractions. Label each force, including the resultant force.

a *A* + *B*

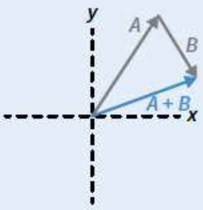
b *B* − *C*

c −*B* − *C*



Working

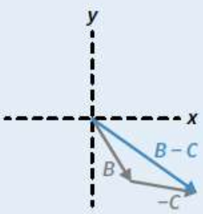
a



Process of thinking

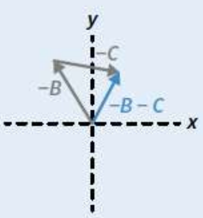
Using the tip-to-tail method, draw vector *A* and then draw vector *B* starting from vector *A*'s tip.

b



Using the tip-to-tail method, draw vector *B* and then draw vector −*C* starting from vector *B*'s tip.

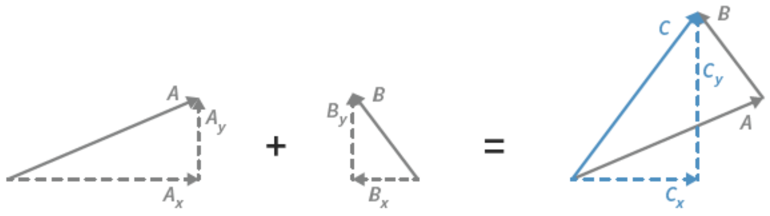
c



Using the tip-to-tail method, draw vector −*B* and then draw vector −*C* starting from vector −*B*'s tip.

Geometrically adding and subtracting vectors

To add or subtract forces geometrically, we must resolve each vector into components that are in perpendicular dimensions and decide which direction is positive for each dimension. We can then add or subtract the vector components in each dimension and the signs will indicate their directions. The results of these additions or subtractions are the perpendicular components of the resultant vector.

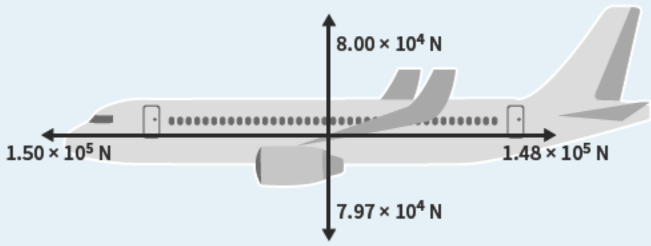


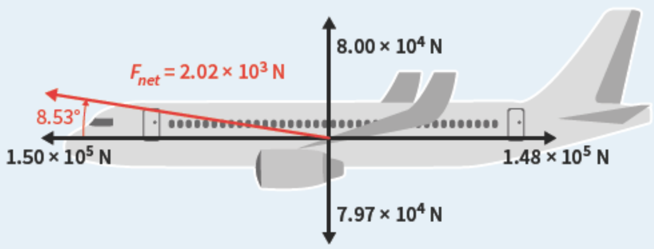
$$A_x + B_x = C_x$$
$$A_y + B_y = C_y$$

Figure 8 The perpendicular components, C_x and C_y, of a resultant vector, C, are the sums of the original vectors' components in each perpendicular dimension.

Worked example 3

Determine the net force acting on the plane. Represent this on a diagram.



Working	Process of thinking
Define to the left and upwards as positive.	Define the positive direction.
$F_x = F_{left} + F_{right} = 1.50 \times 10^5 + (-1.48 \times 10^5) = 2000$ N	Calculate the sum of horizontal forces: $F_{left} = 1.50 \times 10^5$ N, $F_{right} = -1.48 \times 10^5$ N
$F_y = F_{up} + F_{down} = 8.00 \times 10^4 + (-7.97 \times 10^4) = 300$ N	Calculate the sum of vertical forces: $F_{up} = 8.00 \times 10^4$ N, $F_{down} = -7.97 \times 10^4$ N
$F_{net} = \sqrt{F_x^2 + F_y^2} = \sqrt{2000^2 + 300^2} = 2022$ N	Use components to determine the magnitude of the resultant force.
$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{300}{2000}\right) = 8.53°$	Determine the angle of the net force from the left horizontal axis.
Hence, $F_{net} = 2.02 \times 10^3$ N at 8.53° above the left horizontal axis.	
	Represent the net force on the diagram.

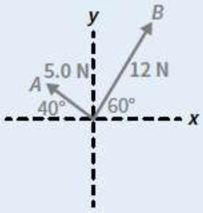
Geometrically adding and subtracting forces that act in different directions in a two dimensional space relies on resolving the vectors into their components. We can then work in the two perpendicular directions independently, as in Worked Example 4, to find the resultant vector.

Worked example 4

Consider the diagram which shows two forces, A and B, acting within a two-dimensional plane.

a Add forces A and B. Provide the magnitude and direction (measured from the x-direction) of the result.

b Subtract force A from force B. Provide the magnitude and direction (measured from the x-direction) of the result.



Working

a The positive directions are to the right and upwards.

$A_x = -5.0 \times \cos(40°) = -3.83$ N

$A_y = 5.0 \times \sin(40°) = 3.21$ N

$B_x = 12 \times \cos(60°) = 6.00$ N

$B_y = 12 \times \sin(60°) = 10.39$ N

$A_x + B_x = -3.83 + 6.00 = 2.17$ N

$A_y + B_y = 3.21 + 10.39 = 13.60$ N

$A + B = \sqrt{F_x^2 + F_y^2} = \sqrt{2.17^2 + 13.60^2} = 14$ N

$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{13.60}{2.17}\right) = 81°$

Hence, $A + B = 14$ N at 81° in an anticlockwise direction from the positive direction of the x-axis.

Process of thinking

Define the positive directions.

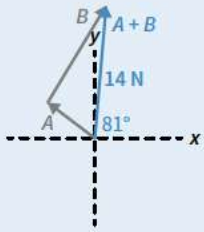
Determine the x- and y-components of both vectors.

Add the components in the x-direction and the components in the y-direction.

Use components to determine the magnitude of the resultant force.

Define the angle of the vector from the positive x-axis.

Using the tip to tail method, this sum looks like:



b $B_x - A_x = 6.00 - (-3.83) = 9.83$ N

$B_x - A_x = 10.39 - 3.21 = 7.18$ N

$B - A = \sqrt{F_x^2 + F_y^2} = \sqrt{9.83^2 + 7.18^2}$ 12 N

$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{7.18}{9.83}\right) = 36°$

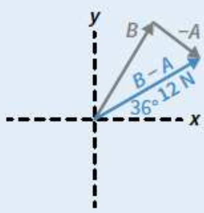
Hence, $B - A = 12$ N at 36° in an anticlockwise direction from the positive direction of the x-axis.

Subtract the previously calculated components of vector A in the x- and y-directions from the components of vector B.

Use components to determine the magnitude of the resultant force.

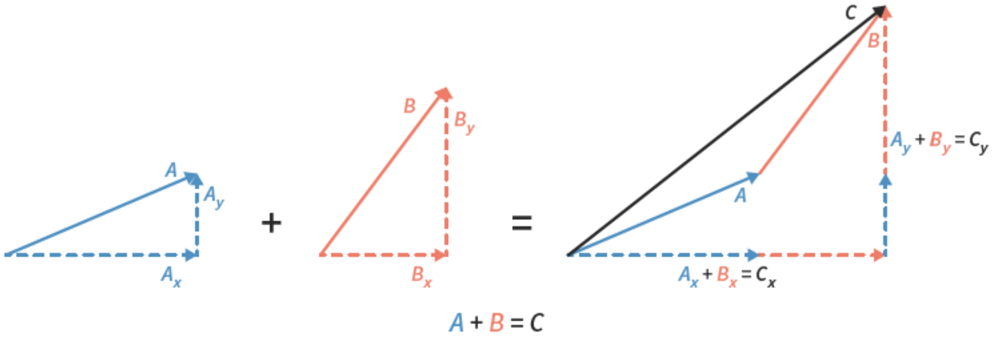
Define the angle of the vector from the positive x-axis.

Using the tip to tail method, this subtraction looks like:



Theory summary

- Forces can be resolved into two perpendicular components via trigonometry.
  - $F_x = F\cos(\theta)$ and $F_y = F\sin(\theta)$ when θ is measured from the *x*-direction.
  - The magnitude and direction of a force can be found from its **perpendicular** components using Pythagoras and trigonometry.
- Graphically, vectors can be added by joining them tip-to-tail.
  - When subtracting, flip the vector being subtracted before adding tip-to-tail.
- To geometrically add (or subtract) forces that act in different directions within a 2D plane, add (or subtract) the components of each vector then use the new components to find the resultant vector.



KEEN TO INVESTIGATE?

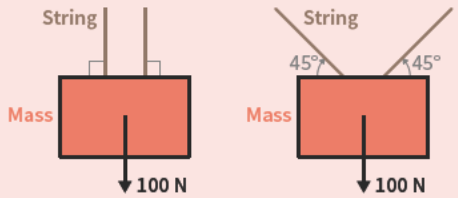
PhET 'Vector Addition' simulation
phet.colorado.edu/en/simulation/vector-addition

YouTube video: Flipping Physics – A Three Force Example of Newton's 2nd Law with Components
youtu.be/IGtbiQt4fCQ

CONCEPT DISCUSSION QUESTION

A builder is deciding how to use two pieces of weak string to support a weight of 100 N. Two possibilities are shown in the included diagram, where the strings are positioned vertically or at angles of 45° to the horizontal. Discuss which configuration is more likely to cause the strings to break.

Answers on page 508



Hints

What is the net force acting on the mass at equilibrium?

How is the 100 N force shared between the two vertical pieces of string?

What component of the 45° forces along the strings act to oppose the 100 N force?

What is the value of the total force along the 45° strings?

9B Questions

THEORY REVIEW QUESTIONS

Use the following force vector diagram to answer Questions 1 and 2.

Question 1

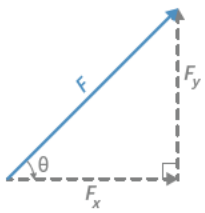
Which force (*A*–*D*) best represents the sum of forces *P* and *Q*?

Question 2

If vector *P* has a magnitude of 3 N and vector *Q* has a magnitude of 5 N, which of the following equations best represents the **subtraction** of vector *Q* from vector *P*? Take to the right as the positive direction.

A −3 − 5 **B** 3 + (−5) **C** (−3) + 5 **D** 3 − (−5)

Use the following force vector diagram to answer Questions 3 and 4.



Question 3

Which of the following options (A–D) correctly identifies the value of F_x and F_y?

	F_x	F_y
A	$F\cos(\theta)$	$F\cos(\theta)$
B	$F\sin(\theta)$	$F\cos(\theta)$
C	$F\cos(\theta)$	$F\sin(\theta)$
D	$F\sin(\theta)$	$F\sin(\theta)$

Question 4

Which of the following equations represents the magnitude of the vector F?

A $\sqrt{F_x^{\,2}+F_y^{\,2}}$

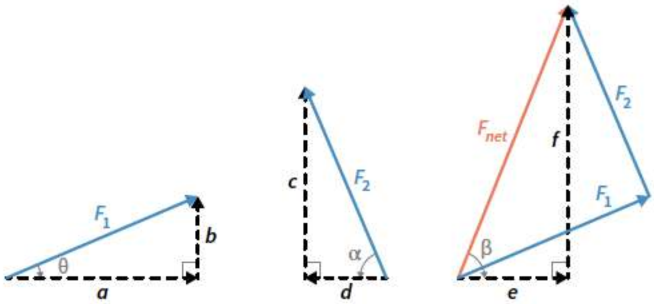
B $\sqrt{F_x+F_y}$

C $F_x^{\,2}+F_y^{\,2}$

D F_x+F_y

Use the following information to answer Questions 5–7.

Two force vectors, F_1 and F_2, are added together to form the force vector F_{net}. F_1 has perpendicular components a and b, F_2 has perpendicular components c and d, and F_{net} has perpendicular components e and f.



Question 5

Which of the following equations correctly represents the horizontal component e?

A $e=a+d$

B $e=a-d$

C $e=b+c$

D $e=a+b+c+d$

Question 6

Which of the following equations correctly represents the vertical component f?

A $f=a+d$

B $f=a-d$

C $f=b+c$

D $f=a+b+c+d$

Question 7

Which of the following equations correctly represents the angle β?

A $\beta=\cos^{-1}\left(\frac{e}{F_{net}}\right)$

B $\beta=\tan^{-1}\left(\frac{f}{e}\right)$

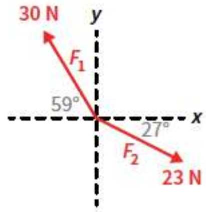
C $\beta=\theta+\alpha$

D $\beta=\theta-\alpha$

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (6 MARKS)

An object is acted on by three forces; F_1, F_2 and F_3. The net force acting on the object is zero. Two of these forces, F_1 and F_2, are shown in the included diagram. Take the positive directions as to the right and upwards.



Prompts

a Knowing that $F_1+F_2+F_3=0$, which of the following equations correctly represents F_3 in terms of the other forces?

A $F_3=F_1+F_2$

B $F_3=-(F_1+F_2)$

C $F_3=F_1-F_2$

D $F_3=F_2-F_1$

b Which of the following options correctly shows the magnitude of the components of F_1 in the x- and y-directions?

	x-component of F_1	y-component of F_1
A	30 × sin(59°)	30 × cos(59°)
B	30 × cos(59°)	30 × cos(59°)
C	30 × sin(59°)	30 × sin(59°)
D	30 × cos(59°)	30 × sin(59°)

c Which of the following options correctly shows the magnitude of the components of F_2 in the x- and y-directions?

	x-component of F_2	y-component of F_2
A	23 × sin(27°)	23 × cos(27°)
B	23 × cos(27°)	23 × cos(27°)
C	23 × cos(27°)	23 × sin(27°)
D	23 × sin(27°)	23 × sin(27°)

d Which of the following equations correctly represents the x-component of F_1+F_2, F_x?

A $F_x=23\times\cos(27°)+(-30\times\cos(59°))$

B $F_x=23\times\cos(27°)+30\times\cos(59°)$

C $F_x=-23\times\cos(27°)+30\times\cos(59°)$

D $F_x=23\times\sin(27°)+(-30\times\sin(59°))$

e Which of the following equations correctly represents the y-component of F_1+F_2, F_y?

A $F_y=23\times\sin(27°)+30\times\sin(59°)$

B $F_y=-23\times\sin(27°)+30\times\sin(59°)$

C $F_y=-23\times\sin(27°)+30\times\cos(59°)$

D $F_y=23\times\sin(27°)+(-30\times\sin(59°))$

f Which of the following options correctly identifies the magnitude of $F_1 + F_2$?

A $F_x + F_y$

B $\sqrt{F_x^2 - F_y^2}$

C $\sqrt{F_x^2 + F_y^2}$

D $F_x^2 + F_y^2$

Question

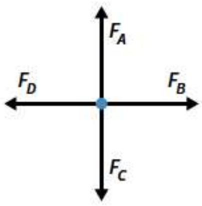
g What is the magnitude and direction of the third force such that the object experiences no net force. (6 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (2 MARKS)

Four students are each pulling on ropes during a four-person tug of war. The magnitude of the forces exerted by the four students are $F_A = 190$ N, $F_B = 230$ N, $F_C = 150$ N and $F_D = 145$ N. The direction of the four forces are shown on the included diagram.



a Which of the following options best represents the magnitude of the net force acting at the centre of the tug of war? (1 MARK)

A 125 N

B 40.3 N

C 93.9 N

D 11.2 N

b Which of the following options best gives the angle that the net force makes with the positive *x*-axis? (1 MARK)

A 25.2°

B 28.1°

C 61.9°

D 64.8°

Adapted from 2018 VCAA Exam Section A Q5

Question 10 (2 MARKS)

When a cyclist is moving around a banked track as in the included image, two forces act on them. The force due to gravity, F_g, acts vertically downwards and the normal force, F_N, acts perpendicular to the slope.

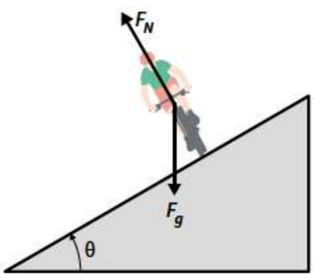


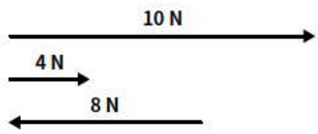
Image: Michal Sanca/Shutterstock.com

On a copy of this diagram show the vector addition of F_N and F_g with a dashed line.

Adapted from 2017 VCAA Exam Section B Q7a

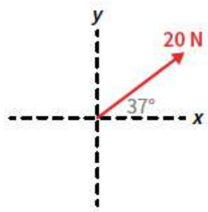
Question 11 (2 MARKS)

Draw and label the resultant force when the three force vectors shown are added together. Your label should include the force magnitude.



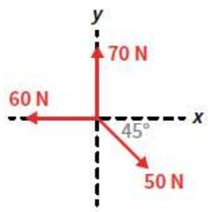
Question 12 (2 MARKS)

For the included force vector, determine the components in the *x*- and *y*-direction.



Question 13 (6 MARKS)

Three forces act on an object as shown in the included diagram.

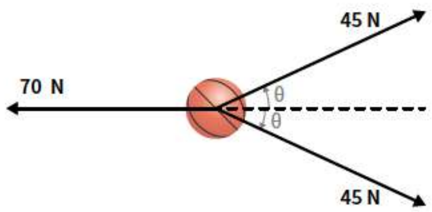


a Calculate the magnitude of the net force acting on the object. (5 MARKS)

b Determine the direction of the net force from the negative *x*-axis. (1 MARK)

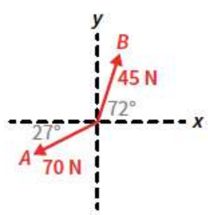
Question 14 (3 MARKS)

In a game of basketball, three different players are pulling on the ball. One players pulls to the left with a force of 70 N, and the other two players pull with a force of 45 N at an angle θ from the horizontal. The ball is in translational equilibrium. Determine the value of θ.



Question 15 (11 MARKS)

Two forces, *A* and *B*, act on an object of mass 5.0 kg.



a Determine the magnitude of the net force on the object. (5 MARKS)

b Determine the magnitude of the acceleration of the object. (2 MARKS)

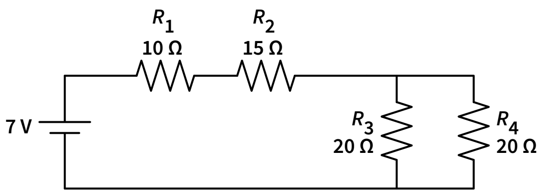
c Calculate the angle that the net force makes with the positive *x*-axis. (2 MARKS)

d Draw a vector representing the net force. Include a magnitude and direction. (2 MARKS)

Previous lessons

Question 16 (3 MARKS)

The following circuit is constructed from 4 resistors and a 7.0 V cell.

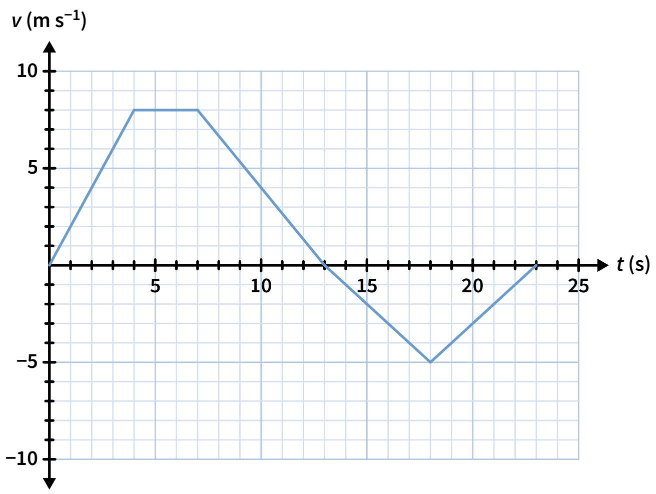


a Determine the effective resistance of the circuit. (2 MARKS)

b Determine the total current flowing through the circuit. (1 MARK)

Question 17 (4 MARKS)

Upon entering Worthwools, Ken Ematics sees that there is only one toilet paper roll left. The included velocity vs time graph represents his motion as he sprints in a straight line to the toilet paper and then walks to the checkout to pay.



a What is Ken's acceleration over the first 4 seconds? (1 MARK)

b By calculating Ken's displacement, determine how far he is from where he started. (3 MARKS)

Key science skills

Question 18 (3 MARKS)

Two school children, Forcia and Victor, are using a piece of string to exert a force on an object at various angles to explore the idea of force vectors. They each use a force transducer to measure the force with which the object is being pulled. They record the force displayed on the force transducer for one experimental setup that is repeated five times and calculate an average. The true value of the force is 5.50 N.

	Meas. 1 (N)	Meas. 2 (N)	Meas. 3 (N)	Meas. 4 (N)	Meas. 5 (N)	Avg. (N)
Forcia	5.43	5.41	5.57	5.50	5.63	5.51
Victor	5.43	5.45	5.42	5.41	5.42	5.43

Identify and explain which set of results is more accurate and which set is more precise.

9C INCLINED PLANES AND CONNECTED BODIES

How does the force produced by a tugboat pull a whole oil tanker with only a piece of rope? What are the relevant forces that make running up a hill much harder than on level ground? This lesson will build on the ideas of Newton's laws to analyse complex situations such as connected bodies and inclined planes.

9A Forces	9B Force vectors in two dimensions	9C Inclined planes and connected bodies	9D Torque	9E Equilibruim

Study design dot point

- apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and reaction forces

Key knowledge units

Inclined planes	2.1.9.3
Connected bodies	2.1.9.4

Formulas for this lesson

Previous lessons		New formulas
9A	$F_g = mg$	$F_{ds} = mg\sin(\theta)$ force down a slope
9A	$F_{net} = ma$	

Definitions for this lesson

connected bodies two or more objects either in direct contact or attached by a string, rope, cable or similar connection

friction a force that resists the relative motion of two surfaces which are in contact

inclined plane a flat surface that is at an angle to the horizontal plane

tension a pulling or stretching force that acts through an object connecting two bodies; the magnitude of the force on both bodies is the same

Inclined planes 2.1.9.3

OVERVIEW

When an object is on an inclined plane, the normal force (F_N) will act perpendicular to the plane, the force due to gravity (F_g) will act vertically down, and the net force (F_{net}) will act parallel to and down the slope. A friction force (F_f) may also be present which acts parallel to the slope against the direction of motion.

THEORY DETAILS

When an object is placed on a hill without a sufficient resistance force acting up the slope, we understand that it will accelerate down the hill. This intuitive knowledge allows us to infer from Newton's second law, $F_{net} = ma$, that the net force on the object must act down the hill. The hill represents an inclined plane: a surface that is at an angle from the horizontal.

When a body is on an inclined plane, there are two forces that always act on it:

- The force due to gravity, F_g, which acts vertically down
- The normal force, F_N, which acts perpendicular to the inclined plane

Furthermore, there may be a friction force, F_f, due to the contact between the body and the inclined plane. This friction force will act in the opposite direction to the motion.

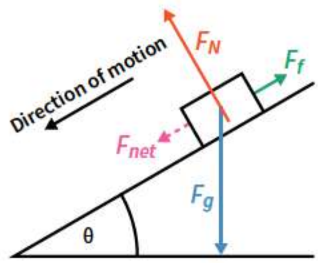


Figure 1 The three forces that may act on a body on an inclined plane; the force due to gravity, the normal force and a friction force. The net force acts in the direction of acceleration, parallel to and down the inclined plane.

For example, when we stand on a hill, it is the friction force between our shoes and the hill that stops us from sliding down to the bottom.

Consider the force due to gravity and the normal force. We can use tip-to-tail vector addition to confirm that the net force will act parallel to and down the plane as shown in Figure 2.

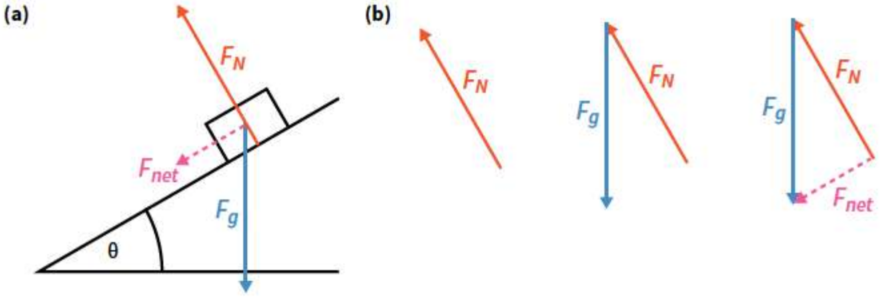


Figure 2 **(a)** The two forces that act on all bodies on an inclined plane, as well as the net force. **(b)** Starting with the normal force, we can add the force due to gravity using a head-to-tail method to find the resulting net force, acting down the slope.

We can quantify the net force by resolving our force vectors such that all forces act parallel or perpendicular to the plane. This will allow us to use addition of vectors in one direction to find the net force.

We use trigonometry to resolve F_g into two components – one which is parallel to and one which is perpendicular to the inclined plane as per Figure 3(a). The angle between F_g and F_N is also the angle of the inclined plane, θ.

Therefore we can conclude that:

- The component of F_g acting parallel to the plane is given by $mg\sin(\theta)$.
- The component of F_g acting perpendicular to the plane is given by $mg\cos(\theta)$.

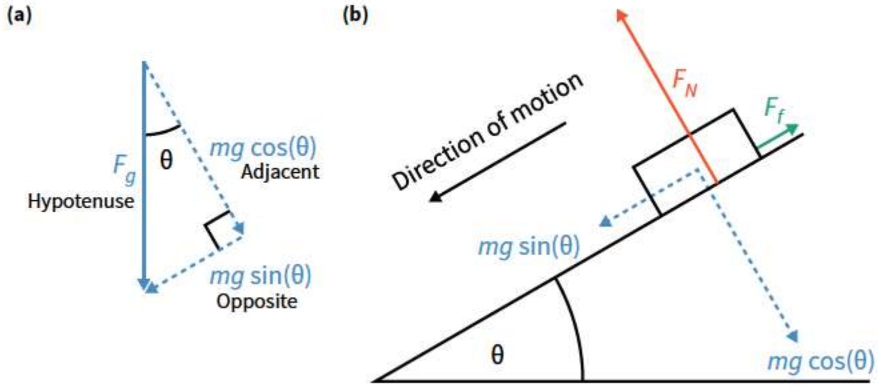


Figure 3 **(a)** The force due to gravity shown as the hypotenuse and its components parallel (opposite) and perpendicular (adjacent) to the inclined plane. **(b)** These components can replace the force due to gravity so that all forces act parallel or perpendicular to the inclined plane.

Given that the object does not accelerate off the plane or into the plane, the normal force must balance the component of gravity that is perpendicular to the plane. That is, the magnitude of the normal force is given by $F_N = mg\cos(\theta)$.

Hence, if there is no friction between the body and the inclined plane then F_{net} will be the component of force due to gravity that acts parallel to the plane, which we will represent with F_{ds} as it is the force that acts down the slope.

$$F_{ds} = mg\sin(\theta).$$

F_{ds} = the component of the force due to gravity acting down the slope (N), m = mass (kg), g = acceleration due to gravity (9.8 m s^{-2})

However, if friction is present, as per Figure 3(b), it will act in the opposite direction to the motion. Then our equation for the net force acting on the body will be:

$$F_{net} = F_{ds} - F_f = mg\sin(\theta) - F_f$$

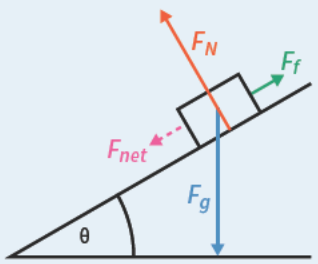
Worked example 1

A block of mass 1.0 kg is placed on an inclined plane angled at 45° to the horizontal. There is a constant frictional force of 2.0 N exerted on the block by the inclined plane.

a **Draw a diagram that shows all the forces acting on the block. Include the net force as a dotted line. Values for each force are not required.**

b **Calculate the magnitude of the normal force acting on the 1.0 kg block.**

c **Calculate the magnitude of the net force acting on the 1.0 kg block**

Working	Process of thinking
a 	Identify the forces acting on the block and in what direction they act: • Gravity – vertically down • Normal – perpendicular to plane • Friction – opposite to motion Also note that the net force acts down the plane.
b $F_N = mg\cos(\theta)$ $F_N = 1.0 \times 9.8 \times \cos(45°)$ $F_N = 6.9$ N	As the block is not accelerating perpendicular to the plane, the normal force must be equal to the component of gravity perpendicular to the plane, $F_N = mg\cos(\theta)$ $m = 1.0$ kg, $g = 9.8$ m s^{-2}, $\theta = 45°$, $F_f = 2.0$ N
c $F_{net} = mg\sin(\theta) - F_f$ $F_{net} = 1.0 \times 9.8 \times \sin(45°) - 2.0$ $F_{net} = 4.9$ N	As the normal force is balanced by the perpendicular component of the force due to gravity, we only need to consider the two forces acting parallel to the plane: • Component of gravity parallel to the plane, F_{ds} • Friction force, F_f Hence we can use $F_{net} = mg\sin(\theta) - F_f$ $m = 1.0$ kg, $g = 9.8$ m s^{-2}, $\theta = 45°$, $F_f = 2.0$ N

Connected bodies 2.1.9.4

OVERVIEW

When two or more bodies are connected or are in direct contact, there is a tension force (T) or a contact force that acts on each object with equal magnitude but in opposite directions. The acceleration of all connected bodies will be equal, and Newton's Second Law can be applied to the whole connected body system or the individual components to find this acceleration or the forces within the system.

THEORY DETAILS

Connected bodies in tension

When two or more bodies are connected by a string, rope, or similar material, and there is a force (or forces) which acts to separate the two bodies, there exists a tension force, T, which acts in both directions pulling the bodies together. This force has the same magnitude for both bodies. In VCE Physics, the string will be considered massless.

You have experienced this tension force if you have ever played a game of tug of war. The rope exerts a tension force on both teams. This force has the same magnitude but acts in the opposite direction on each team, meaning that both teams will be pulled by the rope towards the centre with the same force. The winning team is the team that can exert a greater outwards force than this inwards tension force. See Figure 4.

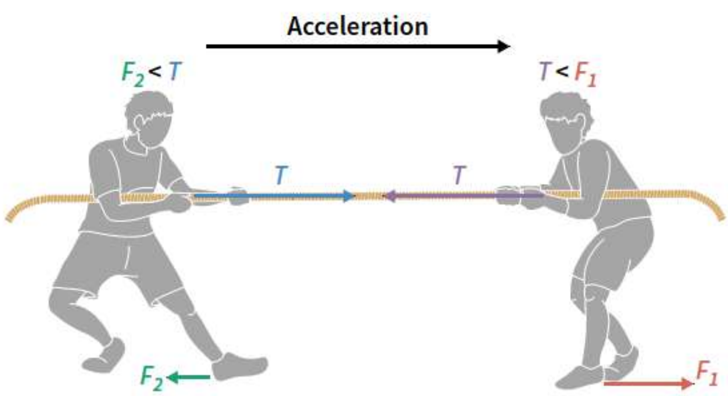


Image: Arak Rattanawijittakorn/Shutterstock.com

Figure 4 A tension force of equal magnitude acts in the opposite direction when playing a game of tug of war. If an outwards force acting on an object is greater in magnitude than the tension force, then the system will accelerate in that direction.

Figure 5 shows a cart, *A*, which is experiencing a pulling force, F_x, to the right and which is towing a block, *B*. Both the cart and the block experience the tension force, *T*, which acts with equal magnitude on both objects but in the opposite direction. In this case block *B* experiences a friction force, but friction will not always be considered in VCE Physics.

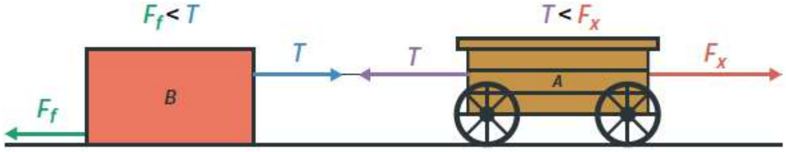


Figure 5 The horizontal forces involved when a cart, *A*, is towing a block, *B*

To analyse the motion of bodies which are connected in tension we are able to apply Newton's Second Law, $F_{net} = ma$, to the entire system and also to each part of the system. A system is an individual or group of interacting bodies that we select to study. So, for example, the different systems that we could apply Newton's second law to in Figure 5 are:

- The cart and the block as a single combined system.
- The individual cart as the system.
- The individual block as the system.

The combined system

When analysing the combined system, we treat the block and the cart as a single object:

- Ignore the tension forces, which are considered 'internal forces' in this case because they have the same magnitude in opposite directions, cancelling each other out.
- Use the sum of all the masses.

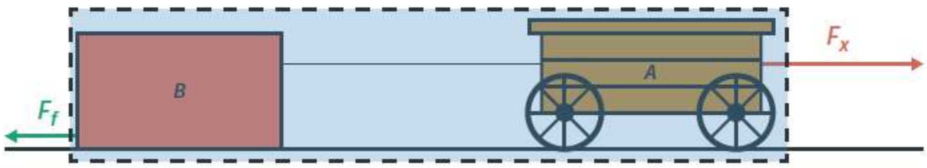


Figure 6 The horizontal forces acting on the combined cart and block system. As tension acts with the same magnitude in opposite directions, they will cancel out and can be ignored. We consider the cart and block as a single mass, and must use their combined mass in calculations.

Take right as the positive direction. Therefore, when analysing the combined system with Newton's Second Law we generate the equations:

- $F_{net} = F_x - F_f$
- $F_{net} = (m_A + m_B) \times a$

The individual cart or block system

When analysing an individual object within the connected body system:

- Consider only the forces acting directly on that object, including the tension force.
- Use only the mass of that object.

Therefore, when analysing the individual cart system with Newton's Second Law we generate the equations:

- $F_{net} = F_x - T$
- $F_{net} = m_A \times a$

When analysing the individual block system with Newton's Second Law we generate the equations:

- $F_{net} = T - F_f$
- $F_{net} = m_B \times a$

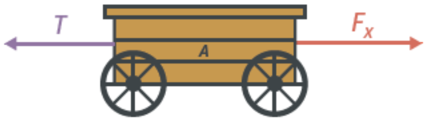


Figure 7 The horizontal forces acting on the individual cart system. Tension must be considered as it is no longer cancelled with the adjacent tension force.

Figure 8 The horizontal forces acting on the individual block system. Tension must be considered as it is no longer cancelled with the adjacent tension force.

Worked example 2

A cart of mass 2.0 kg pulls a block of mass 1.0 kg. The cart is pulled by a force of 10.0 N and there is a constant friction force of 4.0 N that acts on the block.

a Calculate the magnitude of the acceleration of the block.

b Calculate the magnitude of the tension force in the string that connects the cart to the block.

Working	Process of thinking
a $F_{net} = F_x - F_f = 10.0 - 4.0 = 6.0$ N $F_{net} = (m_A + m_B) \times a = (2.0 + 1.0) \times a$ $\therefore 6.0 = (2.0 + 1.0) \times a$ $a = 2.0$ m s^{-2}	$m_A = 2.0$ kg, $m_B = 1.0$ kg, $F_x = 10.0$ N, $F_f = 4.0$ N As we do not know the tension force, we cannot consider the individual block. The acceleration of the block will be the same as the acceleration of the combined system. If we consider the combined system, we can ignore the tension force, and we must use the combined mass of the cart and block.
b Consider the cart: $F_{net} = m_A \times a = 2.0 \times 2.0 = 4.0$ N $F_{net} = F_x - T = 10.0 - T$ $\therefore 4.0 = 10.0 - T$ $\therefore T = 6.0$ N **OR** Consider the block: $F_{net} = m_B \times a = 1.0 \times 2.0 = 2.0$ N $F_{net} = T - F_f = T - 4.0$ $\therefore 2.0 = T - 4.0$ $\therefore T = 6.0$ N	$m_A = 2.0$ kg, $m_B = 1.0$ kg, $F_x = 10.0$ N, $F_f = 4.0$ N, $a = 2.0$m s^{-2} In order to solve an equation that involves the tension force, we must consider an individual object that is connected to the string as the system. The cart or the block can be used. We have shown both methods.

We use a similar approach to answer questions when one or two of the connected masses are hanging via a pulley as per Figure 9. In these types of questions, we can model the system as if it were on a horizontal plane because the pulley simply changes the direction of the tension force. The same principle of applying individual or combined systems to find the desired force or acceleration is still suitable.

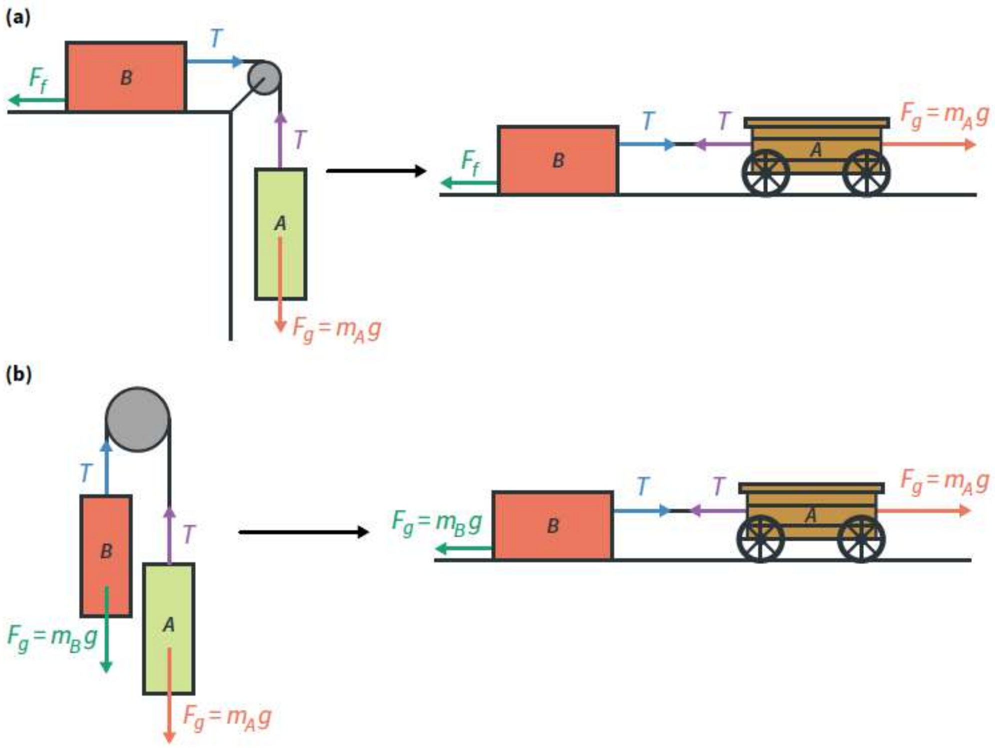


Figure 9 **(a)** The forces involved for a block, A, which is hanging and connected to a block, B, which is on a horizontal surface, can be modelled with all forces acting in a horizontal direction. **(b)** The forces involved when two blocks, A and B, are connected and hanging can be modelled with all forces acting in a horizontal direction.

Connected bodies in contact

Another case we need to consider is connected bodies in contact. In Figure 10(a), a force acts on block B due to its contact with block A, $F_{on\,B\,by\,A}$. By Newton's Third Law there will also be a contact force on block A by block B that is equal in magnitude and opposite in direction, $F_{on\,A\,by\,B}$.

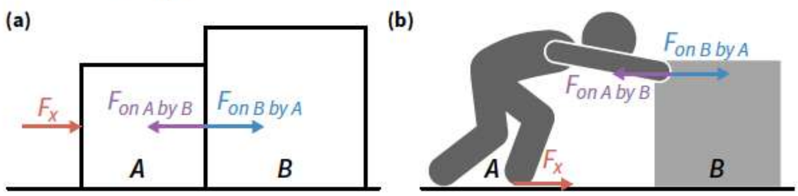


Image: Lemery/Shutterstock.com

Figure 10 **(a)** The horizontal forces involved when a block, A, is being pushed by a force F_x and is in contact with a second block, B. $F_{on\,B\,by\,A}$ is the only force that acts on block B whereas block A experiences force F_x and $F_{on\,A\,by\,B}$. **(b)** A contact force of equal magnitude and opposite direction acts when a person is trying to push a box.

Similar to connected bodies in tension, the way we analyse situations involving connected bodies in contact is to consider the combined system or each individual element. The only difference is that tension is being replaced by the contact force. We can consider:

- Both blocks as a combined system.
- An individual block as the system.

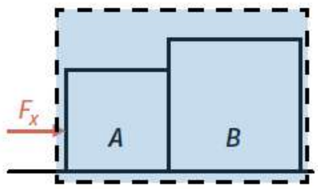


Figure 11 The horizontal forces acting on the whole system. As the contact forces have the same magnitude in opposite directions, they will cancel out and can be ignored. We consider all the bodies as a single mass, and must use their combined mass in calculations.

The combined system

When analysing the combined system, we can treat all bodies as a single object:

- Ignore the contact forces, which are considered 'internal forces' in this case as they have the same magnitude in opposite directions, cancelling each other out.
- Use the sum of all the masses.

Take right as the positive direction. Therefore, when analysing the combined system with Newton's Second Law we generate the equations:

- $F_{net} = F_x$
- $F_{net} = (m_A + m_B) \times a$

If friction is acting on the system, the friction force will act in the opposite direction to the pushing force, F_x.

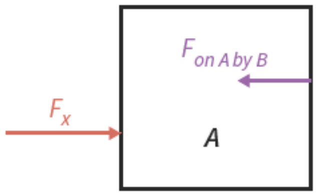


Figure 12 The horizontal forces acting on the block *A* system. The contact force, $F_{on\ A\ by\ B}$, must be considered as it is no longer cancelled by the $F_{on\ B\ by\ A}$ contact force.

The individual body system

When analysing an individual object within the connected body system:

- Consider only the forces acting directly on that object, including the contact force.
- Use only the mass of that object.

Therefore, when analysing the individual block *A* system with Newton's second law we generate the equations:

- $F_{net} = F_x - F_{on\ A\ by\ B}$
- $F_{net} = m_A \times a$

When analysing the other individual block *B* system with Newton's Second Law we generate the equations:

- $F_{net} = F_{on\ B\ by\ A}$
- $F_{net} = m_B \times a$

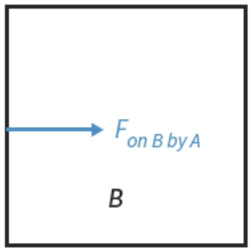
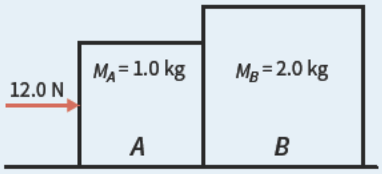


Figure 13 The horizontal force acting on the block *B* system. The contact force $(F_{on\ B\ by\ A})$ must be considered as it is no longer cancelled with the $F_{on\ A\ by\ B}$ contact force.

Worked example 3

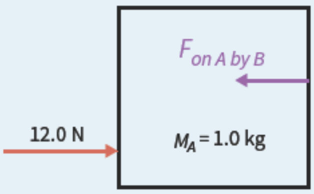
Two blocks, *A* and *B*, are in contact and being pushed by a force of 12.0 N on a frictionless surface. Block *A* has a mass of 1.0 kg and block *B* has a mass of 2.0 kg.



a **Calculate the acceleration of the blocks.**

b **Calculate the magnitude of the force on block *A* by block *B*.**

c **Calculate the magnitude of the force on block *B* by block *A*.**

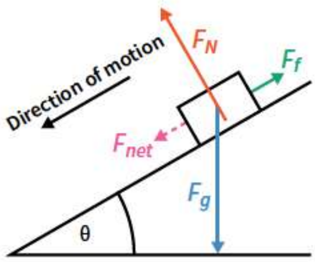
Working	Process of thinking
a $F_{net} = F_x = 12.0$ N $F_{net} = (m_A + m_B) \times a = (1.0 + 2.0) \times a$ $\therefore\ 12.0 = (1.0 + 2.0) \times a$ $a = 4.0$ m s^{-2}	$m_A = 1.0$ kg, $m_B = 2.0$ kg, $F_x = 12.0$ N As we are asked to find the acceleration of the blocks and are given information about their masses and the force acting on them, will work with the combined mass of the blocks.
b  $F_{net} = m_A \times a = 1.0 \times 4.0 = 4.0$ N $F_{net} = F_x - F_{on\ A\ by\ B} = 12.0 - F_{on\ A\ by\ B}$ $\therefore\ 4.0 = 12.0 - F_{on\ A\ by\ B}$ $F_{on\ A\ by\ B} = 8.0$ N	$m_A = 1.0$ kg, $m_B = 2.0$ kg, $F_x = 12.0$ N, $a = 4.0$ m s^{-2} As we are asked to find the contact force on block *A*, we will consider it as an individual system.
c $F_{on\ B\ by\ A} = 8.0$ N	We know that the force on block *B* by block *A* will have the same magnitude but act in the opposite direction. $F_{on\ B\ by\ A} = -F_{on\ A\ by\ B}$

USEFUL TIP

When asked to find an acceleration within a connected body system, we can consider either the combined system or individual elements since all parts of the connected body system will accelerate at the same rate.

When asked to find the tension or contact force within a connected body system, only consider one of the individual components since the tension or contact forces between the individual bodies does not appear in calculations analysing the combined system.

Theory summary



- The net force, F_{net}, acting on a body on an inclined plane acts down the slope.
  - When friction is absent: $F_{net} = F_{ds} = mg\sin(\theta)$
  - When friction is present: $F_{net} = F_{ds} - F_f = mg\sin(\theta) - F_f$
- Tension is the force acting on a body through a rope, string, cable or similar connection.
  - The tension force will act on both of the bodies to which it is attached with the same magnitude but act in opposite directions.
- For connected bodies, we apply Newton's Second Law to the combined system or to individual elements to calculate acceleration or forces.
- When considering the combined system:
  - Use the sum of the individual masses.
  - The tension and contact forces should not appear in calculations.
- When considering the individual components:
  - Use only the mass of the individual component.
  - Make sure to consider the tension or contact forces.

KEEN TO INVESTIGATE?

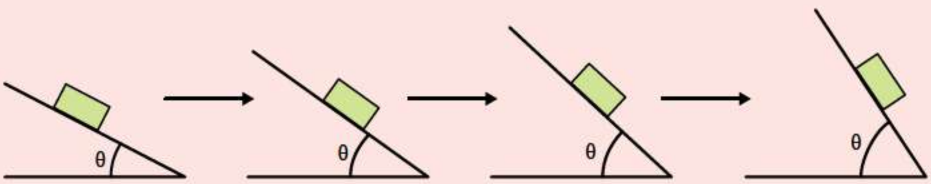
oPhysics 'Static and Kinetic Friction on an Inclined Plane' simulation
ophysics.com/f2.html

PhET 'Ramp: Forces and Motion' simulation
phet.colorado.edu/en/simulation/legacy/ramp-forces-and-motion

YouTube video: High School Physics Explained – The Normal force and the Incline
youtu.be/okn8D1e25fM

CONCEPT DISCUSSION QUESTION

For each of the following forces acting on the block, discuss how both the magnitude and the direction (relative to the horizontal) changes or remains constant as the angle of an inclined plane to the horizontal increases as shown in the diagram.



a Force due to gravity

b Normal force

c Component of the force due to gravity acting down the slope

Answers on page 508

Hints

How do the sides of a force vector triangle change as θ changes?

Does the magnitude of the force depend on the angle of the inclined plane?

What is the direction of the force relative to the inclined plane?

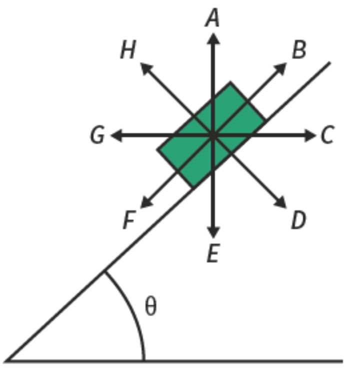
How does the direction of the force change as θ increases?

9C Questions

THEORY REVIEW QUESTIONS

Use the following force vector diagram to answer Questions 1–5.

A block of mass m rests on a **rough** inclined plane angled at θ° to the horizontal as per the included diagram. The force vectors are not to scale.



Question 1

Which of the force vectors (*A*–*H*) is in the same direction as the force due to gravity?

Question 2

Which of the force vectors (*A*–*H*) is in the same direction as the normal force?

Question 3

Which of the force vectors (*A*–*H*) is in the same direction as the friction force when the object is sliding down the incline?

Question 4

The net force can be found by the addition of force vectors in which three directions (*A*–*H*)?

Question 5

Which of the force vectors (*A*–*H*) is in the same direction as the component of the force due to gravity which is parallel to the inclined plane?

Question 6

Which of the following options best gives the value of the net force acting on the block.

A $F_{net} = mg\sin(\theta)$

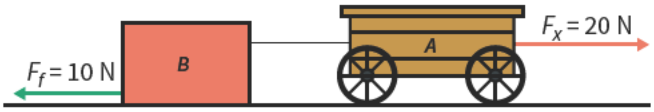
B $F_{net} = mg\sin(\theta) - F_f$

C $F_{net} = mg\cos(\theta)$

D $F_{net} = mg\cos(\theta) - F_F$

Question 7

A cart is being used to pull a block connected by a rope across a surface which provides a constant frictional force, F_f, of 10 N. The cart provides a driving force, F_x, of 20 N to the right, and both the cart and the block have a mass of 10 kg.

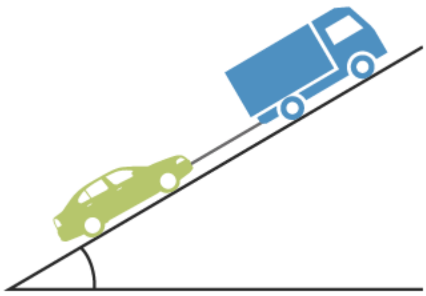


a If asked to find the acceleration of the block, it would be easiest to consider the __________ (whole combined, individual block, individual cart) system as the tension force in the rope __________ (is acting on the block, cancels out).

b If then asked to find the value of the tension force, it would be easiest to consider the __________ (whole combined, individual block or cart) system as the tension force in the rope __________ (is acting on the block and cart, cancels out).

Use the following information to answer Questions 8 and 9.

After a driver on his probationary license crashes his car, it is towed up a hill by a truck with **twice the mass** of the car. The car and truck are connected by a weightless and inextensible rope. The friction force can be ignored.



Question 8

If the tension force can be described as acting down the slope on the truck, then the tension force acting on the car will have __________ (half, the same, double) magnitude and act __________ (up the slope, down the slope).

Question 9

Which of the following best describes the magnitude of the net force acting on each of the masses?

A The net forces acting on the car and the truck are the same.

B The net force on the car is twice as much as the net force on the truck.

C The net force on the truck is twice as much as the net force on the car.

Question 10

Using the word bank, fill in the gaps in the following paragraph. Use each option once.

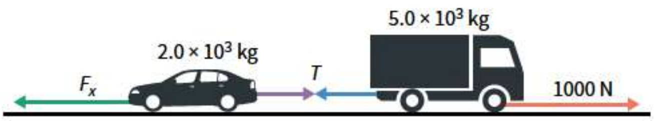
- greater than
- opposite
- same
- equal to
- less than

During a tug of war, an older brother (with a greater mass) is easily able to win and pull his smaller brother across the room. The magnitude of the net force acting on the big brother is __________ the net force acting on the smaller brother and both of these net forces act in the __________ direction. The magnitude of the tension force acting on the bigger brother is __________ the tension force acting on the smaller brother and acts in the __________ direction.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 11 (5 MARKS)

An angry man is using his truck, of mass 5.0×10^3 kg, to pull his neighbours car, of mass 2.0×10^3 kg, to the right across the road. The truck exerts a driving force of 1000 N and the car exerts a driving force in the opposite direction of F_x N, as shown on the included diagram.



The truck and the car accelerate to the right at a rate of 5.0×10^{-2} m s^{-2}.

a What is the magnitude of the net force acting on the truck?

- **A** 2.5×10^2 N
- **B** 1.0×10^2 N
- **C** 3.5×10^2 N
- **D** 2.0×10^2 N

b Which of the following shows an equation representing the net force acting on the truck?

- **A** $F_{net\ truck} = 5.0 \times 10^3 + T$
- **B** $F_{net\ truck} = 1000 - T$
- **C** $F_{net\ truck} = 1000 - T - F_x$
- **D** $F_{net\ truck} = 1000 + T + F_x$

c What is the magnitude of the net force acting on the whole system?

- **A** 2.5×10^2 N
- **B** 3.5×10^2 N
- **C** 1.0×10^2 N
- **D** 1.5×10^2 N

d Which of the following shows an equation representing the net force acting on the whole system?

- **A** $F_{net} = 1000 - T$
- **B** $F_{net} = 1000 - T - F_x$
- **C** $F_{net} = 1000 + T - F_x$
- **D** $F_{net} = 1000 - F_x$

e Determine the magnitude of the tension force, T, and the magnitude of the driving force of the car, F_x. (5 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 12 (6 MARKS)

A block of mass 20 kg is placed on a frictionless inclined plane at 30°. Take acceleration due to gravity, g, as 9.8 m s^{-2}.

a List all the forces acting on the mass. (2 MARKS)

b Determine the magnitude of the component of the force due to gravity acting down the slope, F_{ds}. (2 MARKS)

c Calculate the magnitude of the normal force, F_N. (2 MARKS)

Question 13 (4 MARKS)

A car of mass 2500 kg is being used to tow a 1000 kg boat connected by a metal coupling. The car accelerates at a rate of 2.0 m s^{-2}. Ignore the effects of friction.

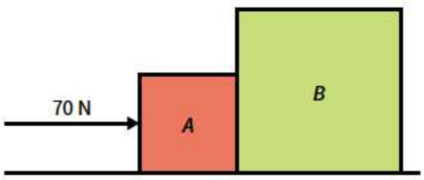
a Determine the driving force of the car which causes it to accelerate, F_d. (2 MARKS)

b Calculate the tension in the metal coupling, T. (2 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 1 Q1/2

Question 14 (5 MARKS)

Two blocks A (3.0 kg) and B (5.0 kg) are in contact and are being pushed on a frictionless surface by a force of 70 N.



a Calculate the acceleration of block B. (2 MARKS)

b Determine the magnitude of the force on block B by block A. (1 MARK)

c What are the direction and the magnitude of the force on block A by block B? (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q8

Question 15 (7 MARKS)

After playing a game of truth or dare, Victoria Smith finds herself skiing down a volcano. The volcano can be modelled as an inclined plane at 15° to the horizontal with a constant friction force of 75 N. Victoria and her skis have a combined mass of 80 kg. Take the acceleration due to gravity, g, to be 9.8 m s^{-2}.

Image: VectorShow/Shutterstock.com

a On a copy of the included diagram, draw and label all of the forces which act on Victoria. Include the net force as a dotted arrow. Values are not required. (4 MARKS)

Image: VectorShow/Shutterstock.com

b Calculate the magnitude of the net force acting on Victoria and the skis. (2 MARKS)

c Determine the acceleration of Victoria and her skis down the volcano. (1 MARK)

Adapted from 2013 VCAA Exam Section A Q1

Question 16 (7 MARKS)

A bus of mass 3500 kg is being used to tow a car of mass 1500 kg at a constant speed. There is a constant friction force of 800 N on the bus and 300 N on the car.

a What is the driving force produced by the bus? (2 MARKS)

b Determine the value of the tension force acting on the car. (1 MARK)

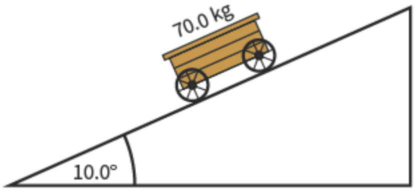
c The bus now increases its driving force so it accelerates at 2.0 m s^{-2}. Calculate the magnitude of the tension force acting on the car. (2 MARKS)

d What is the magnitude and direction of the tension force acting on the bus? (2 MARKS)

Adapted from VCAA 2006 Exam 1 Section A AoS 1 Q1–2

Question 17 (8 MARKS)

After being forced to go shopping with their mum, a young child decides to get revenge and pushes the shopping cart of mass 70.0 kg down a rough hill inclined at 10.0°. Whilst chasing the shopping cart, the mother notices that it is moving down the hill with a constant velocity. Take acceleration due to gravity, g, as 9.8 m s^{-2}.



a What is the net force acting on the cart? (1 MARK)

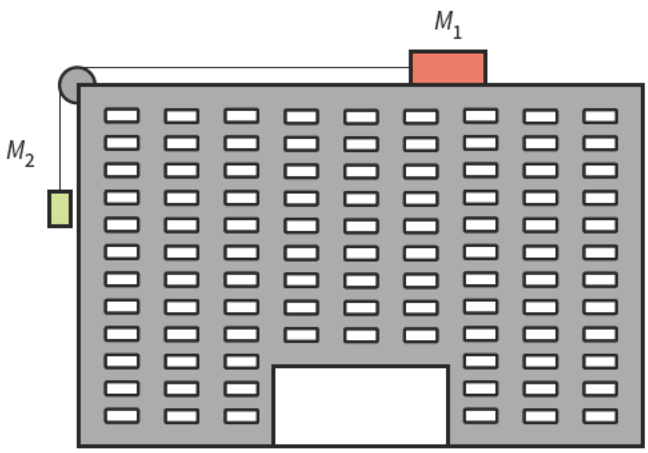
b Determine the **magnitude and direction** of the normal force acting on the car. (3 MARKS)

c Calculate the component of the force due to gravity that acts down the slope. (2 MARKS)

d Determine the magnitude of the friction force acting on the shopping cart. (2 MARKS)

Question 18 (10 MARKS)

Whilst moving houses, a couple must lower a box M_2 (60.0 kg) off the roof of their apartment building. To stop the box accelerating too fast, they use a string and a pulley to connect it to another box M_1 (85.0 kg). The roof is initially a frictionless surface. Take acceleration due to gravity, g, as 9.80 m s^{-2}.



a On the diagram, draw and label all forces that act on each box. Values are not required. (3 MARKS)

b Calculate the magnitude of the acceleration of M_2. (3 MARKS)

c Determine the tension in the string. (1 MARK)

The couple realises that the block will fall too fast, so they add sand to the building roof so that there is a friction force acting on M_1.

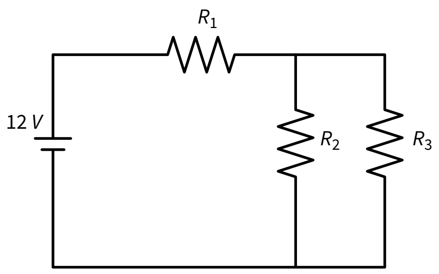
d What is the value of the friction force, F_f, such that M_2 accelerates at 1.0 m s^{-2}. (3 MARKS)

Adapted from 2013 VCAA Exam Section A Q2

Previous lessons

Question 19 (6 MARKS)

A circuit is set up containing a 12 V DC battery as well as three resistors. R_2 and R_3 have resistances of 2.0 Ω and 3.0 Ω, respectively. A student is tasked to determine various values within the circuit.



a Using an ammeter, the student finds that there is a current of 2.0 A through R_3. Determine the voltage drop across R_3. (1 MARK)

b Calculate the value of the current through R_2. (2 MARKS)

c Determine the resistance of R_1. (3 MARKS)

Question 20 (5 MARKS)

The driver of a BMW accelerates from rest at a rate of 7.0 m s^{-2} away from a set of traffic lights. Ignoring his speedometer, the driver uses a calculator in order to determine his speed after accelerating for 5.0 seconds.

a Determine the speed of the BMW after 5.0 seconds. (2 MARKS)

Looking up from his calculator, the driver sees an elephant on the road 75 m ahead. Knowing that his car is able to decelerate at 10.0 m s^{-2}, he then calculates if he will be able to stop in time before hitting the elephant.

b Will the BMW stop before it makes contact with the elephant? Use calculations to support your answer. (3 MARKS)

Key science skills

Question 21 (3 MARKS)

Whilst playing with a toy car and a long ramp, a toddler decides that she will measure the time it takes for the car to reach the bottom of the ramp. The stopwatch, as in the included diagram, has gradation marks every 0.2 seconds. The mechanical nature of the stopwatch consistently measures the times to be 0.6 seconds longer than in reality.

Image: iCreative3D/Shutterstock.com

a What is the uncertainty in the measurements from the stopwatch? (1 MARK)

b Determine the type error that the 0.6 second delay in the stopatch is. Suggest one method that could be used to reduce this error. (2 MARKS)

9D TORQUE

What do a wrench, your biceps, and a door have in common? This lesson will introduce the concept of torque and show how it applies to a variety of common situations. This knowledge will later be used to describe the rotational equilibrium of systems such as seesaws, cranes and bridges.

9A Forces	9B Force vectors in two dimensions	9C Inclined planes and connected bodies	9D Torque	9E Equilibrium

Study design dot point

- calculate torque: $\tau = r_{\perp}F$

Key knowledge unit

Torque	2.1.10.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$\tau = r_{\perp}F$ torque

Definitions for this lesson

torque the turning effect caused by a force at a distance from a pivot point (vector)

Torque 2.1.10.1

OVERVIEW

Torque (τ) is a vector quantity which represents the turning effect created by a force (F) which acts at a perpendicular distance ($r_{\perp}$) from an axis of rotation or pivot point. Torque is measured in newton-metres (N m) and is proportional to the sine of the angle ($\sin(\theta)$) between the line of action of the force and the line between the pivot point and point of application of the force.

THEORY DETAILS

We have explored in previous lessons how forces can cause objects to move in straight lines. A force can also cause objects to rotate. Torque is a quantity that helps us describe the turning effect of a force.

Torque with perpendicular forces

Torque (τ) is the turning effect caused when a force (F) acts at a distance from an axis of rotation ($r_{\perp}$). The pivot point (or axis of rotation) is the point on, or line through, an object about which all other points rotate. For example, the axis of rotation of a bike wheel is the central axle. Torque is a vector, and it can have a clockwise or anticlockwise (also called counterclockwise) direction.

Picture opening a door as in Figure 2 – pulling on the door applies a force (F) which acts perpendicular to the door at a distance ($r_{\perp}$) from the hinges (axis of rotation), so the door experiences a torque.

The maximum torque will act on an object if the force acts perpendicular to the line between the axis of rotation and the location of the applied force. Imagine trying to tighten a nut using a wrench as in Figure 3 – we apply the maximum torque to the bolt by applying a force perpendicular to the wrench.

Image: zimowa/Shutterstock.com

Figure 1 The axis of rotation of a bicycle wheel is its centre.

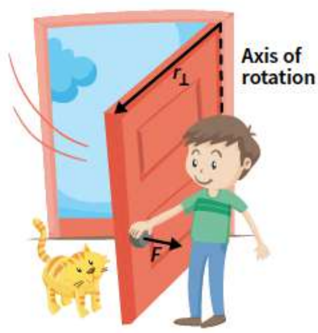


Image: BlueRingMedia/Shutterstock.com

Figure 2 A door experiences torque when a force, F, acts perpendicular to the door at a distance, $r_{\perp}$, from the hinges.

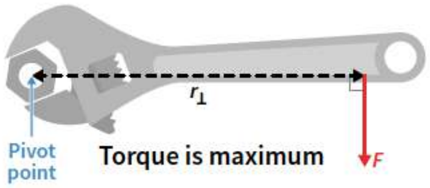


Figure 3 The maximum torque on a nut will occur when the force on a wrench acts perpendicular to the line between the pivot point and where the force is applied.

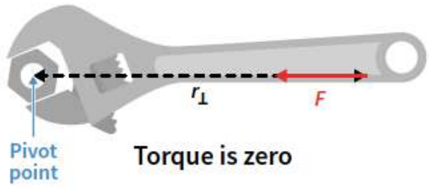


Figure 4 The torque on a nut will be zero when the force on a wrench acts parallel to the line between the axis of rotation and where the force is applied.

On the other hand, if the force is directed towards the pivot point from its point of application, as in Figure 4, then the torque will be zero and no rotation will occur.

For a perpendicular force, torque is directly proportional to the magnitude of the force and the perpendicular distance to the pivot point. So, to increase the torque acting on an object we could

- increase the magnitude of the force.
- increase the distance from the axis of rotation that the force acts.

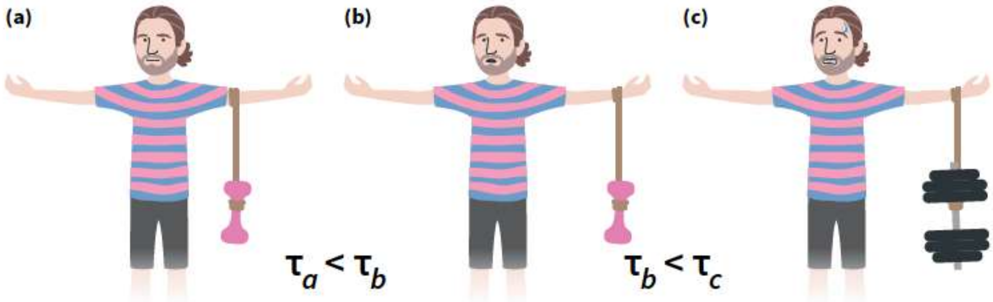


Figure 5 The torque on a body will be larger when the distance to the pivot point is larger ($\tau_a < \tau_b$) and when the magnitude of the force is larger ($\tau_b < \tau_c$).

$$\tau = r_\perp F$$

τ = torque (N m), $r_\perp$ = perpendicular distance (m), F = force (N)

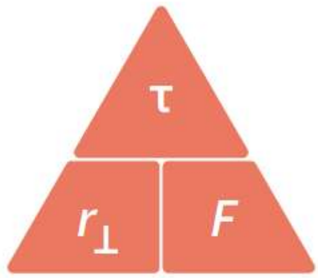
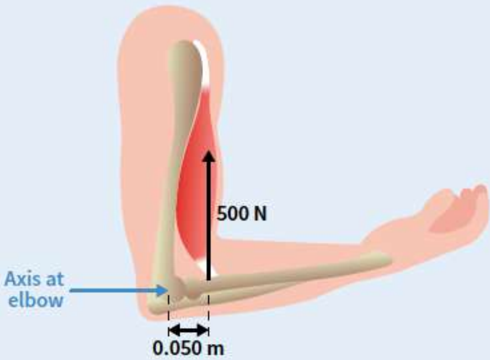


Figure 6 Formula triangle for torque

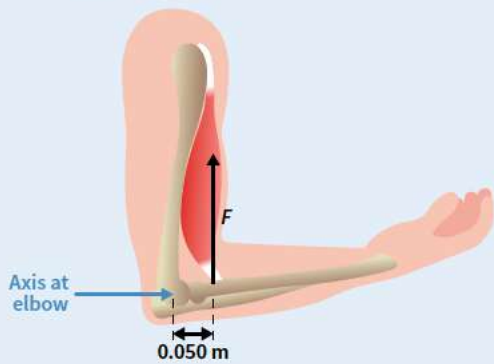
Worked example 1

While at the gym, a physicist and an anatomist decide to calculate the torque acting on an athlete's forearm. They know that the athlete's **right** biceps is able to generate 500 N of force which acts perpendicular to the forearm at a distance of 0.050 m from the elbow joint.

a Determine the torque acting on the athlete's right forearm by the biceps.



b The athlete's left biceps can produce 40 N m of torque on their forearm. The force created by the biceps acts perpendicular to the forearm at the same distance from the elbow joint as previously, 0.050 m. Determine the magnitude of the force generated by the athlete's left biceps.



Working	Process of thinking
a $\tau = r_{\perp}F$	As the force is acting perpendicular to the forearm, we will use the equation $\tau = r_{\perp}F$.
$\tau = 0.050 \times 500 = 25$ N m	$F = 500$ N, $r_{\perp} = 0.050$ m, $\tau = ?$
$\tau = 25$ N m anticlockwise	As torque is a vector, include direction.
b $\tau = r_{\perp}F$	As the force is acting perpendicular to the forearm, we will use the equation $\tau = r_{\perp}F$.
$40 = 0.050 \times F$ $F = \frac{40}{0.050} = 800$ N $F = 8.0 \times 10^2$ N	$\tau = 40$ N m, $r_{\perp} = 0.050$ m, $F = ?$

Torque with non-perpendicular forces

It is common for the force acting on an object to not act perpendicular to the line between the pivot point and the point of action of the force. In this case, the force does not induce the maximum torque. There are two ways we can calculate the magnitude of the torque in this situation:

- **Approach 1:** calculate the perpendicular component of the force
- **Approach 2:** calculate the lever arm

Figure 7 A force acting in a non-perpendicular direction

Calculating the perpendicular component of the force

The component of the force which acts perpendicular to the object can be found using trigonometry.

$$\sin(\theta) = \frac{opposite}{hypotenuse} = \frac{F_{\perp}}{F}$$

$$F_{\perp} = F\sin(\theta)$$

Figure 8 The perpendicular component of a force acting in a non-perpendicular direction is $F_{\perp} = F\sin(\theta)$.

From this, the torque acting on the object is given by $\tau = rF_{\perp} = rF\sin(\theta)$.

Calculating the lever arm

The lever arm is the perpendicular line between the direction of the force and the axis of rotation. This represents the distance from the axis of rotation if the force were to act in a perpendicular direction. It can be found using trigonometry.

$$\sin(\theta) = \frac{opposite}{hypotenuse} = \frac{r_{\perp}}{r}$$

$$r_{\perp} = r\sin(\theta)$$

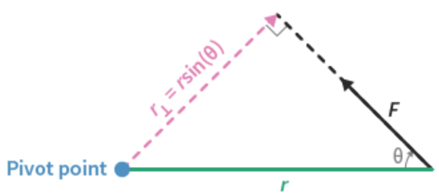


Figure 9 The lever arm when a force is acting in a non-perpendicular direction is $r_{\perp} = r\sin(\theta)$.

From this, the torque acting on the object is given by $\tau = r_{\perp}F = r\sin(\theta)F$.

Both of these methods are valid and yield the same final equation for the magnitude of the torque for a non-perpendicular force:

$$\tau = rF\sin(\theta)$$

Worked example 2

Whilst lifting a weight in the gym, an athlete's biceps applies a force of 400 N to their forearm at an angle of 40°. The force acts at a distance of 0.050 m from the elbow joint.

Determine the torque applied to the athlete's forearm by the biceps.

Working	Process of thinking
$\tau = rF\sin(\theta)$	As the force is not perpendicular to the forearm, we will use the equation $\tau = rF\sin(\theta)$.
$\tau = 0.050 \times 400 \times \sin(40°) = 12.9$ N m	$F = 400$ N, $r_{\perp} = 0.050$ m, $\theta = 40°$, $\tau = ?$
$\tau = 13$ N m anticlockwise	As torque is a vector, include direction.

Torque due to multiple forces

In situations where multiple forces are acting on the same object, we can find the resultant or net torque by considering the direction in which each torque acts – clockwise or anticlockwise. The net torque acting on an object is the sum of the torques acting on it.

It is common to consider the anticlockwise direction as the positive direction and then use the sign of your final answer to determine the direction of the resultant torque. We will follow this convention in our working. However, as long as the positive direction is consistent, it will not matter which direction you choose.

If we consider the example shown in Figure 10, the force F_2 will result in an anticlockwise torque acting on the object, whereas the force F_1 will result in a clockwise torque acting on the object. Taking the anticlockwise direction as positive, we can state that $\tau_{net} = \tau_2 - \tau_1 = r_2F_2 - r_1F_1$.

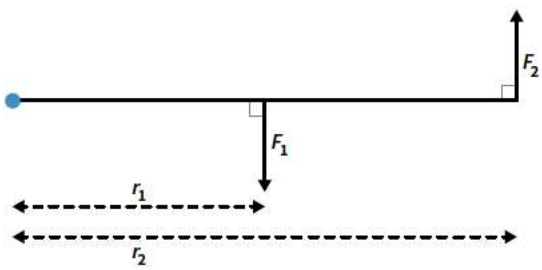


Figure 10 Two forces, F_1 and F_2, acting on an object at perpendicular distances of r_1 and r_2 respectively

Imagine yourself holding two masses as in Figure 11, but one is significantly heavier than the other. This larger mass causes a larger force to act at the same distance from the pivot point compared to the smaller mass. Hence the larger mass induces a greater torque on your body.

Figure 11 The torque on a body will be larger when a greater force is applied at the same radial distance.

Figure 12 The torque on a body will be larger when the distance to the pivot point is larger.

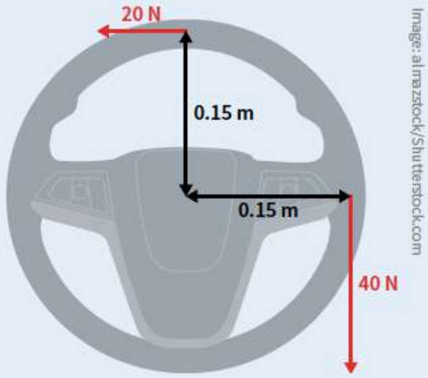
Now picture yourself holding two equal masses: one close to your body and one far away as in Figure 12. The mass which is further away applies the same force, however it induces a greater torque on your body.

Worked example 3

While on her learner permit, a young driver applies a force of 40 N vertically downwards on the right-hand side of the steering wheel of her car. Her instructor, knowing that the learner is going to crash, applies a force of 20 N directly to the left on the top of the steering wheel.

Both forces are perpendicular and at a distance of 0.15 m from the axis of rotation of the steering wheel.

Find the net torque acting on the steering wheel.



Working

Take the anticlockwise direction as positive.

$\tau_{net} = \tau_2 - \tau_1 = r_\perp F_2 - r_\perp F_1$

$\tau_{net} = 0.15 \times 20 - 0.15 \times 40 = -3.0$ N m

$\tau_{net} = 3.0$ N clockwise

Process of thinking

F_1 acts to create a clockwise torque and F_2 acts to create an anticlockwise torque.

We will take the anticlockwise direction to be positive and use the equation $\tau = r_\perp F$.

$F_1 = 40$ N, $F_2 = 20$ N, $r_\perp = 0.15$ m, $\tau_{net} = ?$

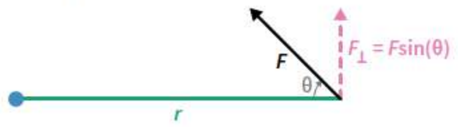
As torque is a vector, remember to include a direction in your answer.

Theory summary

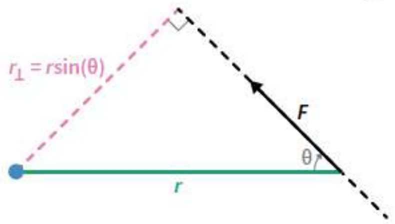
- Torque is a turning effect about an object's axis of rotation or pivot point.
  - $\tau = r_\perp F$
  - Measured in newton-metres (N m)
  - Torque is a vector with a direction of rotation.
- The torque on an object will be at a maximum when the force acts perpendicular to the line between the pivot point and the location of the applied force.

- The torque will be zero when the force acts parallel to the line between the pivot point and the location of the applied force.

- When torque acts at a non-perpendicular angle to the object, there are two approaches that can be used to calculate the torque.
  - **Approach 1:** Find the component of the force which acts perpendicular to the object. $\tau = rF_{\perp}$



  - **Approach 2:** Find the lever arm as the perpendicular line between the line of action of the force and the pivot point. $\tau = r_{\perp}F$



  - Both of these approaches result in the equation $\tau = rF\sin(\theta)$
- When multiple forces are acting on the same object, the net torque can be found by the addition of the individual torques and considering the direction in which they act.

KEEN TO INVESTIGATE?

YouTube video: Engineering Explained – Horsepower vs Torque
youtu.be/u-MH4sf5xkY

YouTube video: CrashCourse – Torque
youtu.be/b-HZ1SZPaQw

CONCEPT DISCUSSION QUESTION

When lifting heavy objects, we are often told to lift with the knees and not the back to avoid back pain. An example of this can be seen in the included image. Discuss how lifting with the knees is safer than lifting with our back. Relate your answer to the force, angle and distance to the pivot point with the torque experienced by the lower back.

Answers on page 508

Image: elenabsl/Shutterstock.com

Hints

What force is acting to create a torque on the person lifting?

Where does this force act and where is the pivot point?

Is the distance between the pivot point and the point where the force is applied the same in the two scenarios?

How does the angle between the back and the force differ in the two scenarios?

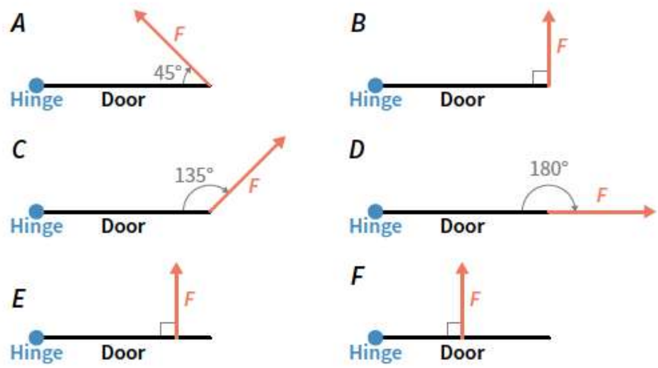
How does the angle of application of a force relate to the torque produced?

9D Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–4.

Whilst trying to open their home door, a teenager decides they will experiment by pulling the door open with a force of constant magnitude but in different directions and locations along the door. The six different situations (*A*–*F*) are shown in the included diagram.



Question 1

Which of the situations (*A*–*F*) results in the **minimum** magnitude of torque acting on the door?

Question 2

Which of the situations (*A*–*F*) results in the **maximum** magnitude of torque acting on the door?

Question 3

Fill in the gaps in the following paragraph.

The magnitude of the torque acting on the door in situation *A* is __________ (less than/greater than/the same as) the torque acting on the door in situation *C*.

Question 4

Fill in the gaps in the following paragraph.

The magnitude of the torque acting on the door in situation *E* is __________ (less than/greater than/the same as) the torque acting on the door in situation *F*.

Question 5

A black belt is practicing their kicks and provides a force to their bag at an angle of θ_1.

Which of the following options correctly identifies the component of the force perpendicular to the bag, $F_\perp$, and the perpendicular line between the line of action of the force and the pivot point, $r_\perp$?

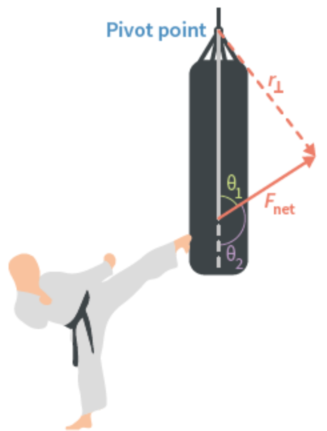


Image: ASAG Studio/Shutterstock.com

	$F_\perp$	$r_\perp$
A	$F\sin(\theta_1)$	$r\cos(\theta_2)$
B	$F\cos(\theta_1)$ and $F\cos(\theta_2)$	$r\cos(\theta_1)$ and $r\cos(\theta_2)$
C	$F\sin(\theta_1)$ and $F\sin(\theta_2)$	$r\sin(\theta_1)$ and $r\sin(\theta_2)$
D	$F\sin(\theta_2)$	$F\sin(\theta_2)$

Question 6

A young child is helping her parents build some IKEA furniture which involves using a torque wrench to tighten a bolt. The child notices her parents apply a 10 N force perpendicular to the end of the 20 cm long wrench.

Which of the following alternatives would provide the same torque to the IKEA bolt? *(Select all that apply)*

I 20 N acting on a 40 cm wrench

II 20 N acting on a 10 cm wrench

III 5 N acting on a 10 cm wrench

IV 5 N acting on a 40 cm wrench

Question 7

Two 18-year-old P platers are comparing their cars on a Saturday night at a kebab shop. They discover that one of their cars has a peak engine torque which is twice as great as the other car.

Which of the following statements is true?

A The car with greater torque will always accelerate faster than the car with less torque.

B The car with greater torque will be able to produce a greater rotational force in the engine than the car with less torque.

Question 8

After changing the wheel on his road bike, Lance uses his hand to spin the wheel anticlockwise before grabbing the wheel and bringing it to rest, as shown in the diagram.

Image: zimowa/Shutterstock.com

Fill in the gaps in the following paragraph to describe this process.

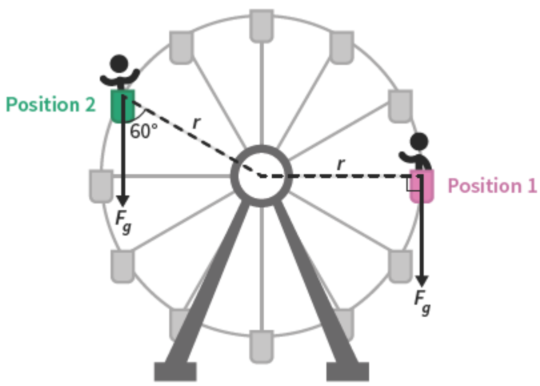
Whilst spinning the wheel anticlockwise, Lance provides __________ (a downwards/an upwards) force which acts to create __________ (a clockwise/an anticlockwise) torque.

When bringing the wheel to rest, Lance provides __________ (a downwards/an upwards) force which acts to create __________ (a clockwise/an anticlockwise) torque.

DECONSTRUCTED EXAM-STYLE QUESTIONS

Question 9 (5 MARKS)

Two friends are on a Ferris wheel and are positioned in different passenger cars. Each friend has a mass of 77 kg. The force due to gravity from the friend in the first position acts at an angle of 90°, whereas the force from the friend in the second position acts at an angle of 60°. The distance from the axis of rotation and the point of action of both forces is *r* metres.



The resultant torque acting on the Ferris wheel is 805 N m in the clockwise direction. Take the anticlockwise direction as positive, and the value of $g = 9.8$ m s^{-2}. Ignore the mass of the Ferris wheel.

Prompts

a Which of the following equations represents the force due to gravity acting on a single friend?

A $F_g = 77 \times 9.8$

B $F_g = (77 + 77) \times 9.8$

C $F_g = 77 \times 9.8 \times h$

D $F_g = 77$

b Which of the following represents the torque acting on the Ferris wheel from the force at position 1?

A $\tau_1 = r \times F_g \times \cos(90°)$ clockwise

B $\tau_1 = r \times F_g \times \cos(90°)$ anticlockwise

C $\tau_1 = r \times F_g$ clockwise

D $\tau_1 = r \times F_g$ anticlockwise

c Which of the following represents the torque acting on the Ferris wheel from the force at position 2?

A $\tau_2 = r \times F_g \times \sin(60°)$ clockwise

B $\tau_2 = r \times F_g \times \sin(60°)$ anticlockwise

C $\tau_2 = r \times F_g$ clockwise

D $\tau_2 = r \times F_g$ anticlockwise

d Which of the following shows an equation for the net torque acting on the Ferris wheel as a result of the two forces? Note that the anticlockwise direction is positive.

A $\tau_{net} = r \times F_g - r \times F_g \times \cos(60°)$

B $\tau_{net} = r \times F_g \times \sin(60°) - r \times F_g$

C $\tau_{net} = r \times F_g \times \sin(60°)$

D $\tau_{net} = r \times F_g - r \times F_g \times \sin(60°)$

Question

e What is the radius, r, of the Ferris wheel? (5 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 10 (4 MARKS)

At the job site, Travis is tasked with undoing a series of bolts with a wrench. Having studied physics on the weekend, Travis' knowledge of torque leads him to conclude that to remove the bolt he will have to apply a perpendicular force of 125 N at a distance of 25.0 cm from the axis of rotation of the bolt.

a Determine the magnitude of the torque required to remove the bolt. (2 MARKS)

b Unfortunately, Travis is unable to find a wrench that is 25.0 cm long, and must instead use one which is 35.0 cm long. Calculate the magnitude of the minimum force Travis must exert on the end of the wrench such that the bolt will be removed. (2 MARKS)

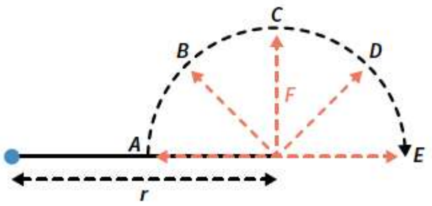
Question 11 (2 MARKS)

Whilst getting home after a hardcore gym session, a bodybuilder must open his door without exceeding a torque of 1200 N m, or the door will break. The bodybuilder knows he will push perpendicular to the door with a force of 900 N.

What is the maximum distance from the hinges of the door the bodybuilder can push so that the door will not break?

Question 12 (3 MARKS)

Describe how the magnitude of the torque on an object changes as the direction of the force changes from A to E as shown in the included diagram.



Question 13 (7 MARKS)

Sarah is walking home after a long day of work when she gets caught out by the rain. Suddenly a gust of wind causes a force of 25 N to act at an angle of 120° to her umbrella. Take the pivot point to be where Sarah is holding the umbrella, 85 cm from where the force is acting.

Image: GertjanVH/Shutterstock.com

a Find the magnitude and direction of the torque acting on Sarah's umbrella when viewed from in front of her. (3 MARKS)

b If the force acting on the umbrella was increased by a factor of 2, by what factor would the torque increase? Calculations are not required. Explain your answer. (2 MARKS)

c For the maximum torque to act on the umbrella, what direction would the force need to act on the umbrella? Explain your answer. (2 MARKS)

Question 14 (3 MARKS)

On a construction site, an excavator is used to lift a 500 kg rock. The rock in the bucket of the excavator is positioned 5.0 m from the axis of rotation, corresponding to a 4.0 m horizontal distance. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Image: Dmitry Kalinovsky/Shutterstock.com

Calculate the magnitude and the direction of the torque acting on the excavator.

Question 15 (7 MARKS)

In the process of starting some planes' engines, the propeller must be manually rotated.

In the scenario shown in the photo, a force of 150 N is applied downwards at 70° to the propeller and at a distance of 0.90 m from the axis of rotation. However, due to a constant resistance within the engine, a torque opposing this can be modelled as the result of a 50 N force acting upwards and perpendicular to the propeller at a distance of 0.60 m from the axis of rotation.

a Determine the magnitude and direction of the net torque acting on the propeller. (4 MARKS)

b The engine properly starts when the net torque acting on the propeller is 100 N m. If the same force were to be applied to the propeller, calculate the angle it must be applied at so that the propeller properly starts. (3 MARKS)

Previous lessons

Question 16 (5 MARKS)

a Discuss the function and operation of a residual-current device in relation to safety. (3 MARKS)

b Give two examples of scenarios in which a residual-current device would be activated. (2 MARKS)

Question 17 (8 MARKS)

An ant of mass 2.0×10^{-6} kg is attempting to cross a tightrope in order to reach some food. Whilst crossing the tightrope, a gust of wind causes a force, F_w, to act vertically upwards on the ant with a force of 2.5×10^{-5} N. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Image: designer_an/Shutterstock.com

a What is the magnitude and direction of the force due to gravity acting on the ant? (2 MARKS)

b Copy the included diagram, and draw and label the force vectors representing the force due to gravity, F_g, and the force due to the wind, F_w. (3 MARKS)

c Calculate the magnitude of the acceleration of the ant. (3 MARKS)

Key science skills

Question 18 (5 MARKS)

Susie is attempting to better understand the idea of torque so she can easily open beverage cans, and decides that she will conduct an experiment. Whilst changing the magnitude of the force she is applying perpendicular to a bottle opener, she records the torque acting on the bottle cap with an imprecise torque sensor.

a For this experiment, determine the independent variable, the dependent variable and a controlled variable. (3 MARKS)

b Susie wants to **reduce the random error** associated in each of her measurements. What is one change she could make to her experiment to achieve this? (1 MARK)

c What is one way Susie could reduce the **effect** of random errors on her results? (1 MARK)

9E EQUILIBRIUM

When building a structure like a bridge or a building, it is critical that the structure neither accelerates nor rotates. This lesson uses what we now understand about force and torque to solve for forces that act on a structure that is in equilibrium.

9A Forces	9B Force vectors in two dimensions	9C Inclined planes and connected bodies	9D Torque	9E Equilibrium

Study design dot point

- investigate and analyse theoretically and practically translational forces and torques in simple structures that are in rotational equilibrium

Key knowledge unit

Equilibrium	2.1.11.1

Formulas for this lesson

Previous lessons		New formulas
9A	$F_g = mg$	No new formulas for this lesson
9A	$F_{net} = ma$	
9D	$\tau = r_{\perp} F$	

Definitions for this lesson

angular acceleration the rate of change of angular velocity per unit time

angular velocity the rate of rotation per unit time

equilibrium the state of a system when it is in both translational and rotational equilibrium

rotational equilibrium the state of a system when the torques on the system sum to zero

translational equilibrium the state of a system when the forces on the system sum to zero

Equilibrium 2.1.11.1

OVERVIEW

Equilibrium is the state of balance a system achieves when the system is in both translational equilibrium (net force is zero) and rotational equilibrium (net torque is zero).

THEORY DETAILS

Translational equilibrium

Translational equilibrium describes the state of a system with zero net force acting on it.

Condition for translational equilibrium:

$$F_{net} = 0$$

As such, the linear acceleration is zero and the velocity is constant. Objects that are not in translational equilibrium will have a non-zero acceleration.

In Lesson 9B, we learned that forces (or components of forces) in perpendicular directions are independent of each other. For this reason, we can resolve forces (if necessary) into horizontal (x-direction) and vertical (y-direction) components and then create two separate translational equilibrium equations.

Condition for translational equilibrium:

$$\Sigma F_x = 0 \text{ and } \Sigma F_y = 0$$

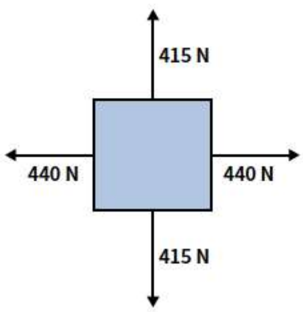


Figure 1 The forces in both a horizontal and a vertical direction are balanced. As such the object is in translational equilibrium.

Rotational equilibrium

Rotational equilibrium describes the state of a system with zero net torque acting on it. This means that the **angular** acceleration is zero and the angular velocity is constant.

Condition for rotational equilibrium:

$$\Sigma\tau = 0$$

If the net torque is zero, the sum of clockwise torques acting on the system is equal to the sum of anticlockwise torques acting on the system.

Condition for rotational equilibrium:

$$\Sigma\tau_{clockwise} = \Sigma\tau_{anticlockwise}$$

For an object in rotational equilibrium, the torque is balanced when measured **around any point**. This means that any point can be treated as the pivot point for the purpose of calculating torques.

Equilibrium

Equilibrium occurs when an object is in both rotational and translational equilibrium. Mathematically, this is the case when:

Conditions for equilibrium:

$$\Sigma F = 0 \text{ and } \Sigma\tau = 0$$

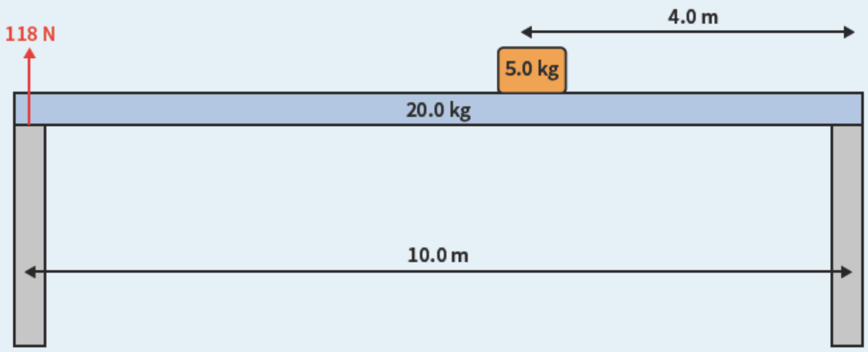
For structures like bridges and buildings to **remain** at rest then they must satisfy the conditions of equilibrium. We can use these mathematical equations to solve for unknown forces that act on an object or structure.

When there is only **one unknown force**, it is simplest to use the translational equilibrium equation to solve for that force as demonstrated in Worked Example 1. Alternatively, we could calculate the one unknown force using the rotational equilibrium equation. However, in general this is more complicated.

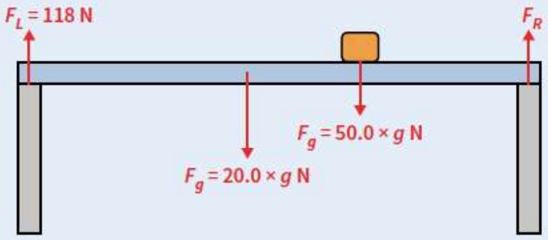
Worked example 1

A uniform beam with a length of 10.0 metres and a mass of 20.0 kg is supported by a column at each end. There is a block of mass 5.0 kg resting 4.0 metres from the right-hand column. The force on the beam by the left-hand column is known to be 118 N.

Calculate the magnitude of the force on the beam by the right-hand column.



Working



Process of thinking

Identify all of the forces acting on the beam.

Take upwards as the positive direction.

$F_{net} = 0 \therefore F_L - F_g - F_B + F_R = 0$

$118 - 20.0 \times 9.8 - 5.0 \times 9.8 + F_R = 0$

$118 - 196 - 49 + F_R = 0$

$F_R = 127$ N

Write the translational equilibrium equation. In this case we have forces in the vertical direction only.

Substitute known values into the equation and solve for the unknown force.

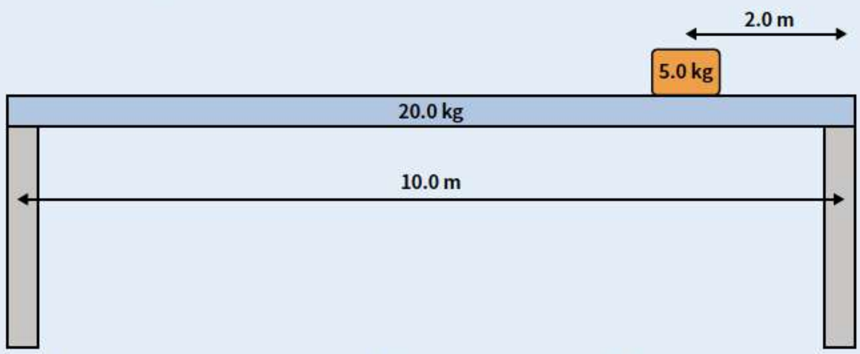
When there are two unknown forces in the same direction, we need a second equation that relates the forces to be able to solve for both of them. This is when the rotational equilibrium equation is most useful as demonstrated in Worked Example 2.

USEFUL TIP

When constructing the rotational equilibrium equation for an object that has multiple unknown forces acting on it, use a point where one of the unknown forces is acting as the pivot point to calculate the torques. This means the lever arm for that unknown force is zero, which eliminates that force from the equation.

Worked example 2

A uniform beam with a length of 10.0 metres and a mass of 20.0 kg is supported by a column at each end. There is a block of mass 5.0 kg resting 2.0 metres from the right-hand column.



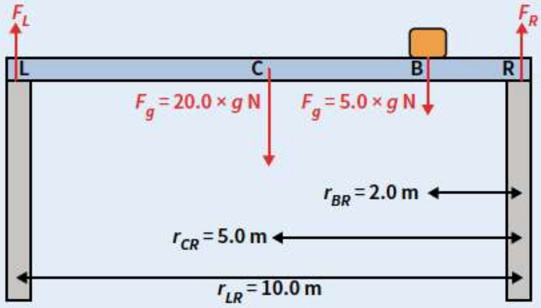
a Calculate the magnitude of the force on the beam by the left-hand column.

b Calculate the magnitude of the force on the beam by the right-hand column.

Working

Process of thinking

a



Identify all of the forces acting on the beam and their locations. Treat the force on the beam due to gravity as acting at the centre (C).

$\Sigma\tau_{anticlockwise} = \Sigma\tau_{clockwise}$

As there are two unknown forces, write the rotational equilibrium equation.

Consider the torques measured around point R:

Choose the point of application of the unknown force that we are not solving for (in this case, R) as the pivot point.

$r_{CR} \times F_g + r_{BR} \times F_B = r_{LR} \times F_L$

$5.0 \times 20.0 \times 9.8 + 2.0 \times 5.0 \times 9.8 = 10.0 \times F_L$

$F_L = 107.8 = 108$ N

Substitute known values into the equation and solve for the unknown force.

b Take upwards as the positive direction.

Now there is only one unknown force (F_L) so we can use the translational equilibrium equation.

$F_{net} = 0 \ \therefore F_L - F_g - F_B + F_R = 0$

$107.8 - 20.0 \times 9.8 - 5.0 \times 9.8 + F_R = 0$

$F_R = 137.2 = 137$ N

Substitute known values into the equation and solve for the unknown force.

When there are two unknown forces and the forces have components in both directions, the rotational equilibrium equation and the translational equilibrium equation in both directions need to be used as demonstrated in Worked Example 3.

In VCE Physics, it can be assumed that any point of contact between a structure (such as the plank in Worked Example 3) and a wall or the ground behaves like a frictionless pivot. This means that the connection can exert forces on the structure but does not prevent rotation around that point.

Worked example 3

A pot plant with a mass of 4.0 kg is resting at the end of a uniform plank with a length of 0.80 m. The plank has a mass of 0.50 kg and it is supported by a frictionless pivot connection at the wall and a rope from the wall. The rope connects to the plank 0.20 m from the wall and it makes an angle of 60° with the horizontal.

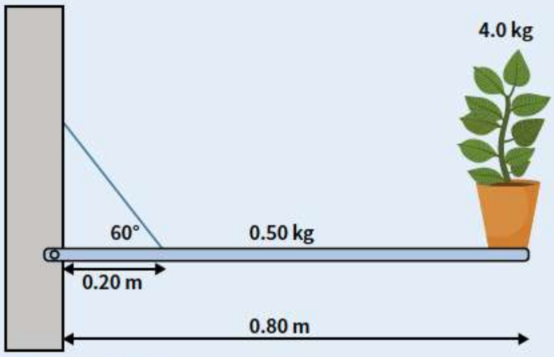


Image: MicroOne/Shutterstock.com

a Calculate the magnitude of the tension force in the rope.

b Calculate the magnitude of the vertical component of the force acting on the plank by the wall.

c Calculate the magnitude of the horizontal component of the force acting on the plank by the wall.

Working

Process of thinking

a

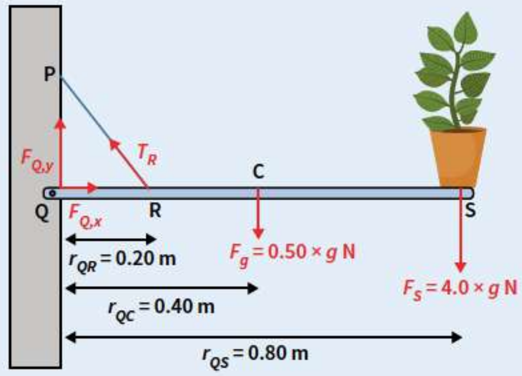


Image: MicroOne/Shutterstock.com

Identify all of the forces acting on the plank and their locations. Treat the force on the plank due to gravity as acting at the centre (C).

$\Sigma\tau_{anticlockwise} = \Sigma\tau_{clockwise}$

As there are two unknown forces (force from the wall and the tension force in the rope), write the rotational equilibrium equation.

Consider the torques measured around point Q:

$r_{QR}T_{R,y} = r_{QC}F_g + r_{QS}F_S$

Choose the point of application of the unknown force that we are not solving for (in this case, Q) as the pivot point. $T_{R,y}$ represents the vertical component of the tension from the rope.

$0.20 \times T_{R,y} = 0.40 \times 4.9 + 0.80 \times 39.2$

$T_{R,y} = 166.6$ N

Substitute known values into the equation and solve for the vertical component of the tension force.

$F_g = m_{plank}g = 0.50 \times 9.8 = 4.9$ N.

$F_S = m_{pot}g = 4.0 \times 9.8 = 39.2$ N.

$T_{R,y} = T_R \times \sin(60°)\ \therefore 166.6 = TR \times \sin(60°)$

$T_R = 192.4 = 1.9 \times 10^2$ N

Use trigonometry to relate the vertical component of the tension to the magnitude of the tension in the rope.

b Take upwards as the positive direction.

$F_{net} = 0\ \therefore F_{Q,y} + T_{R,y} - F_g - F_S = 0$

Now there is only one unknown force ($F_{Q,y}$) in the vertical direction so we can use the translational equilibrium equation in the vertical direction.

$F_{Q,y} + 192.4 - 4.9 - 39.2 = 0$

$F_{Q,y} = 148.3 = 1.5 \times 10^2$ N

Substitute known values into the equation and solve for the unknown force. From part **a**, we have $F_g = 4.9$ N and $F_S = 39.2$ N.

c Take the positive direction as to the right.

$F_{net} = 0\ \therefore F_{Q,x} - T_{R,x} = 0$

Now there is only one unknown force ($F_{Q,x}$) in the horizontal direction so we can use the translational equilibrium equation in the horizontal direction.

$F_{Q,x} - 192.4 \times \cos(60°) = 0$

$F_{Q,x} = 96$ N

Substitute known values into the equation and solve for the unknown force.

Theory summary

- Equilibrium is achieved when the object is in translational equilibrium and rotational equilibrium.
- Translational equilibrium occurs when $F_{net} = 0$. This means that
  - the sum of forces in the x-direction is zero and the sum of forces in the y-direction is zero.
  - the translational acceleration is zero.
- Rotational equilibrium occurs when $\tau_{net} = 0$ at all points. This means that
  - the sum of clockwise torques equals the sum of anticlockwise torques.
  - the rotational acceleration is zero.

KEEN TO INVESTIGATE?

oPhysics 'Equilibrium Problem: Bar Supported by Cable'
ophysics.com/r6.html

PhET 'Balancing Act' simulation
phet.colorado.edu/en/simulation/balancing-act

YouTube video: Flipping Physics – Rotational Equilibrium Introduction
youtu.be/zwZ6OLv4ksA

CONCEPT DISCUSSION QUESTION

Place a pencil on your two forefingers like so and try to move one hand independently towards the other. Experiment with different starting positions, pencils, pens, and rulers. In all cases, your fingers should end up touching with the object balanced in the middle. Using the concept of equilibrium, discuss why this occurs and what might happen if you added an imbalance to the object by tying a battery or similar weight to one end.

Answers on page 508

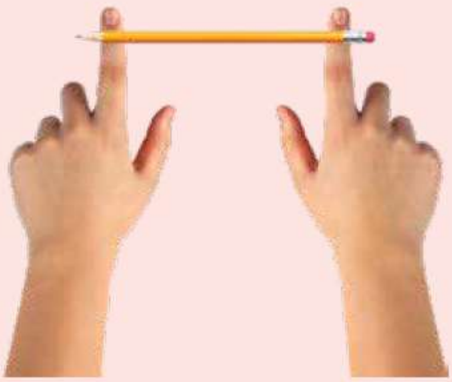


Image: k_samurkas/Vitaly Zorkin/Shutterstock.com

Hints
What forces and torques are acting in this system?
Where are they being measured from?
Have you considered the centre of mass and how it might change?

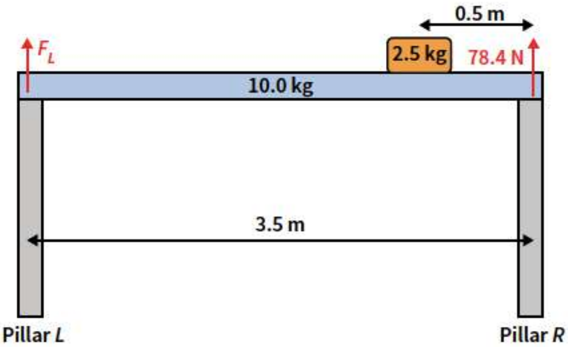
9E Questions

Take the gravitational field strength, g, to be 9.8 N kg^{-1} for all questions in this lesson.

THEORY REVIEW QUESTIONS

Question 1

In the following situation, do you require the rotational equilibrium equation to calculate the unknown force at Pillar *L*?



A Yes

B No

Question 2

In the following situation, do you require the rotational equilibrium equation to calculate the unknown tension force in the rope? The force from the pillar is also unknown.

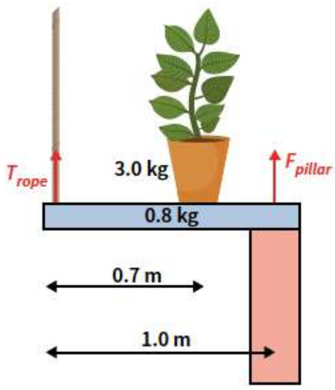


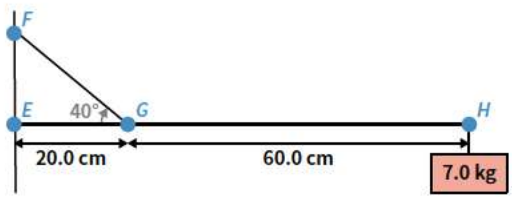
Image: MicroOne/Shutterstock.com

A Yes

B No

Question 3

In the following situation, a rigid massless beam is connected by a frictionless pivot to a wall at point *E*. Do you require the rotational equilibrium equation to calculate the tension force in the rope *FG*?



A Yes

B No

[redacted]

Question 4

A massless beam is supported by a rope (at point *A*) suspended from the ceiling and a massless bench (at point *B*). A stack of books with mass 10 kg rests on the beam at point *C*. The magnitude of the tension in the rope, T_{rope}, and the force from the bench, F_B, are unknown. Which point (*A*, *B*, or *C*) should be used as the pivot point when calculating torques to solve for F_B using only the rotational equilibrium equation?

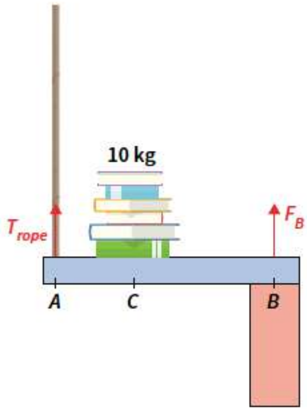
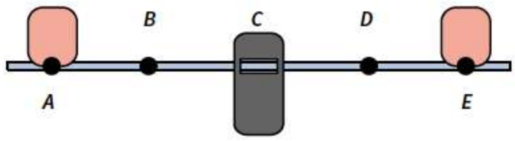


Image: VikiVector/Shutterstock.com

Use the following information to answer Questions 5 and 6.

Points *A* to *E* represent different positions on a balance. The masses are the same and at the same distance from the pivot point *C*. As such, the balance is in equilibrium.



Question 5

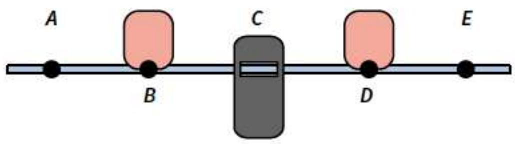
Around which point(s) is the net torque equal to zero? *(Select all that apply)*

Question 6

When considering the torques around the centre (*C*), find the direction of the torques due to the blocks at *A* and *E*.

	Direction of torque around *C* due to force by block at *A*	Direction of torque around *C* due to force by block at *E*
A	clockwise	clockwise
B	anticlockwise	clockwise

Question 7



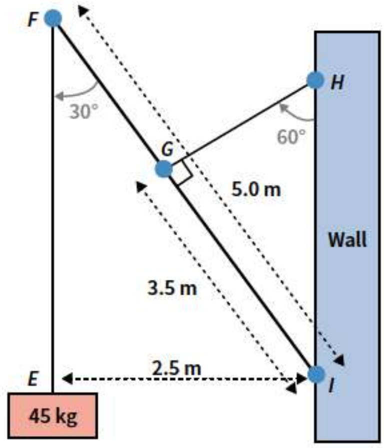
Identify the correct direction of the torques due to the blocks around point *E*.

	Direction of torque around *E* due to force by block at *B*	Direction of torque around *E* due to force by block at *D*
A	clockwise	clockwise
B	anticlockwise	anticlockwise
C	anticlockwise	clockwise
D	clockwise	anticlockwise

DECONSTRUCTED EXAM-STYLE QUESTION

Question 8

A uniform beam *FI* of mass 10 kg and length 5.0 m is attached to the wall with a frictionless pivot at point *I* and is held up by a massless cord *GH*. This beam suspends a mass of 45 kg from point *F*.



Adapted from 2015 VCAA Exam Section B Detailed study 2 Q10

Prompts

a Which of the following expressions represents the magnitude of the torque (in N m) on the beam *FI* around the point *I* due to the 45 kg mass that is suspended?

A $2.5 \times 45 \times g$

B $2.5 \times \sin(30°) \times 45 \times g$

C $5.0 \times 45 \times g$

D $5.0 \times 45 \times g \times \cos(30°)$

b Which of the following expressions represents the magnitude of the torque (in N m) on the beam *FI* around the point *I* due to the tension, T_{GH}, in cord *GH*?

A $3.5 \times T_{GH}$

B $3.5 \times T_{GH} \times \cos(30°)$

C $3.5 \times \sin(30°) \times T_{GH}$

D $1.75 \times T_{GH} \times \sin(30°)$

c Which of the following expressions represents the magnitude of the torque (in N m) on the beam *FI* around the point *I* due to the mass of the beam *FI*?

A $1.25 \times 10 \times g$

B $2.5 \times 10 \times g$

C $2.5 \times 10 \times g \times \cos(30°)$

D $5.0 \times \sin(30°) \times 10 \times g$

Question

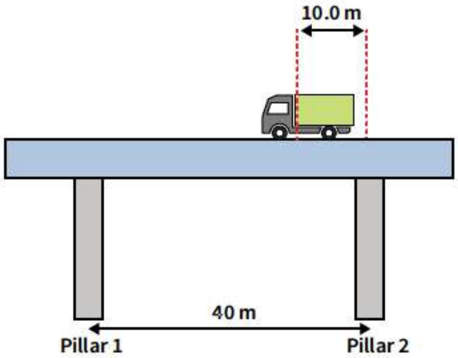
d Calculate the magnitude of the tension force in the cord *GH*. (3 MARKS)

EXAM-STYLE QUESTIONS

This lesson

Question 9 (6 MARKS)

A truck with a mass of 6.0 tonnes is sitting upon a uniform concrete slab which has a mass of 40.0 tonnes. The slab rests evenly on two pillars a distance of 40 m apart. The truck's centre of mass is 10.0 m from one of the pillars.

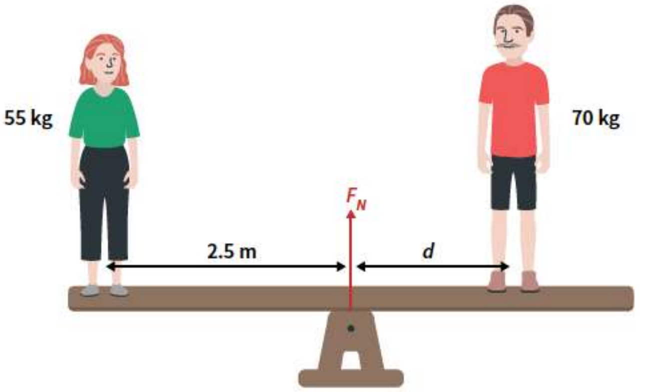


a Calculate the forces on each pillar when the truck is not on the slab. (2 MARKS)

b Calculate the total force on each pillar when the truck is on the slab. (4 MARKS)

Question 10 (5 MARKS)

Two people, one with a mass of 55 kg and the other with a mass of 70 kg are standing on a see-saw. The 55 kg person is 2.5 m from the fulcrum (pivot point).

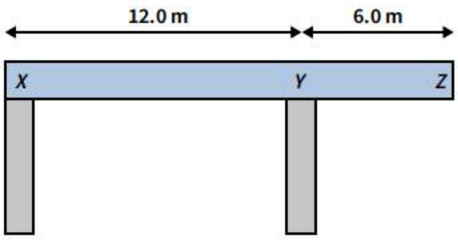


a At what distance, *d*, from the centre of the see-saw should the 70 kg person stand such that that the see-saw is balanced? (3 MARKS)

b Determine the magnitude of the force on the see-saw by the fulcrum, F_N, now that it is balanced. Ignore the mass of the see-saw. (2 MARKS)

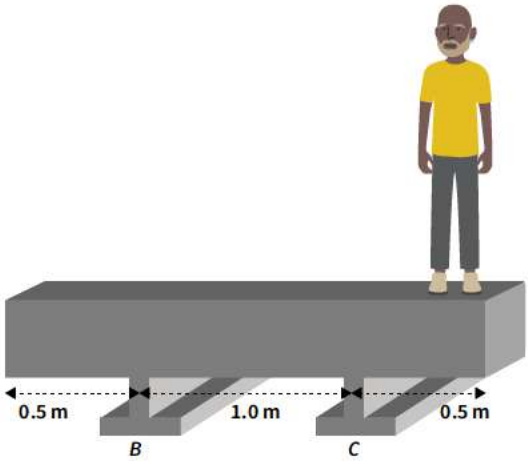
Question 11 (2 MARKS)

A uniform concrete slab is being placed onto two pillars and a structural engineer is attempting to determine the stability of the structure. The slab has a mass of 2000 kg and a length of 18.0 m.



Calculate the force on the pillar at point *X*.

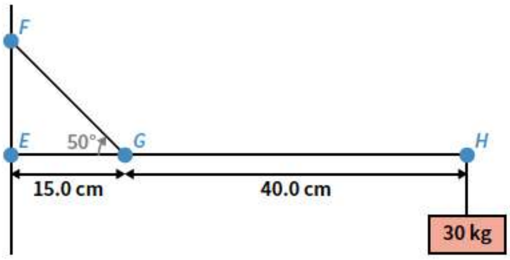
Question 12 (2 MARKS)



A 75 kg man stands on the end of a uniform 60 kg bench which is 2.0 m long. What is the magnitude of the force on the support at point *C*?

Question 13 (4 MARKS)

A 30 kg mass is hanging from a uniform 55.0 cm beam supported by a cable *FG* such that the system is in equilibrium. Point *E* is a frictionless pivot. The cable makes an angle of 50° with the horizontal. Ignore the mass of the beam.



a What is the magnitude of the net torque acting on the beam about the point *E*? (1 MARK)

A 294 N

B 162 N m

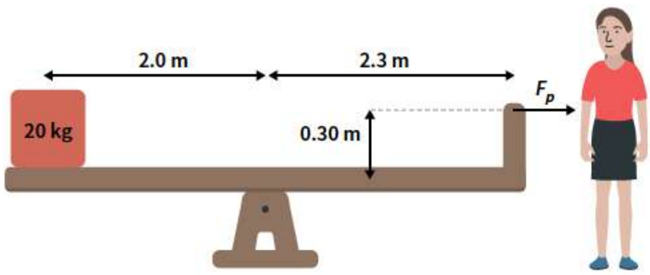
C 118 N m

D 0.0 N m

b Calculate the magnitude of the horizontal force acting on the beam *EH* at point *E*. (3 MARKS)

Question 14 (2 MARKS)

This see-saw is constructed with a lip at the end 2.3 m from the fulcrum (pivot point). It is counterbalanced by a 20 kg block that is 2.0 m from the fulcrum on the other side of the see saw. The woman provides a horizontal force on the lip of the see-saw at a height of 0.30 m, marked as F_p on the diagram.

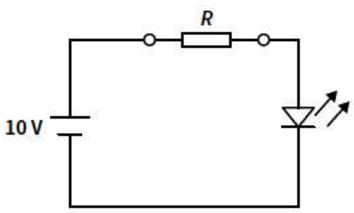


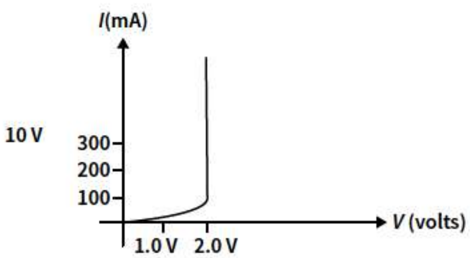
Assuming all parts of the see-saw are weightless, calculate the magnitude of the force F_p such that the see-saw is in equilibrium.

Previous lessons

Question 15 (3 MARKS)

Some students build a circuit in order to power a light-emitting diode (LED). The power is supplied by a 10 V battery and the power dissipated in the LED is 0.35 W.





Using the circuit diagram and the current-voltage characteristic for the LED shown, calculate the resistance of the resistor, *R*.

Question 16 (4 MARKS)

In a tug of war, team A provides a force of 4000 N and team B provides a force of 4020 N. Team A has a mass of 300 kg and team B has a mass of 305 kg. Ignore the mass of the rope.

Image: Miceking/Shutterstock.com

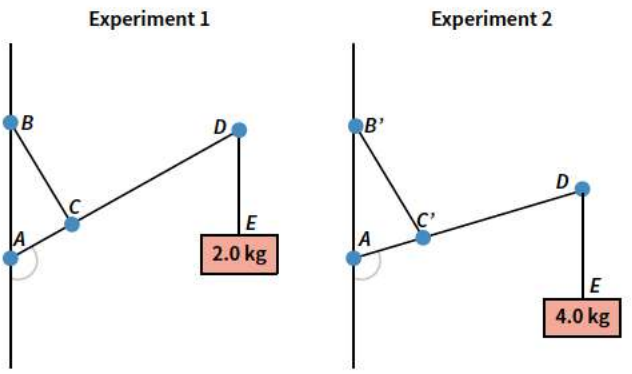
a Copy the situation and draw a force diagram, treating each team as one object. (2 MARKS)

b Calculate the magnitude and direction of the system's acceleration. (2 MARKS)

Key science skills

Question 17 (2 MARKS)

Julia is attempting to calculate the capacity of the cord *BC*. She takes increasingly heavy weights and then remeasures how long the cord *BC* is.



She conducts a large range of experiments using multiple weights and many repetitions, however she notices an abnormality in her data. When Julia calculates the mass of the block from the data, in every experiment it was 0.5 kg greater than the mass used in the experiment.

Explain which type of error might be causing this difference between the theoretical and experimental mass of the block.

CHAPTER 9 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

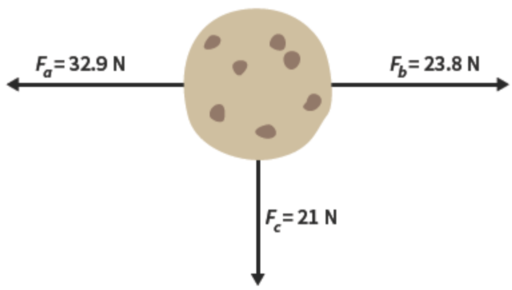
SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Emma is pulling apart a cookie with three forces, $F_a = 32.9$ N, $F_b = 23.8$ N and $F_c = 21$ N. Calculate the magnitude of the resultant force on the cookie. Forces are not drawn to scale.



A 77 N

B 30 N

C 23 N

D 21 N

Adapted from 2018 VCAA Exam Section A Q5

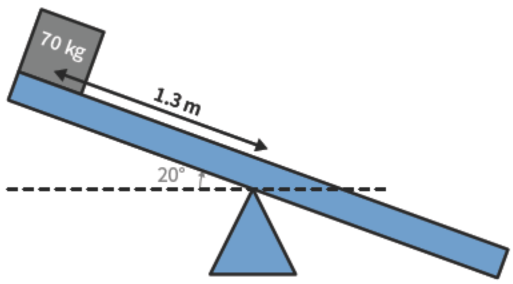
Question 2

A rally driver decelerates a 1.20 tonne car to a stop by providing a breaking force of 2.54×10^4 N. Calculate the magnitude of the car's acceleration.

A 21.2 m s^{-2} **B** 25.6 m s^{-2} **C** 212 m s^{-2} **D** 256 m s^{-2}

Question 3

A 70 kg block is placed at the top of a see-saw whilst it is being held in its highest position. The block's centre of mass is 1.3 m from the centre of the see-saw and the see-saw is at an angle of 20° from the horizontal.



The magnitude of the torque around the centre of the see-saw is:

A 838 N m

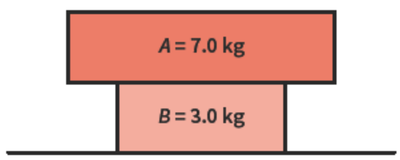
B 645 N m

C 892 N m

D 305 N m

Question 4

A person places brick A of 7.0 kg on top of brick B of 3.0 kg as per the diagram. What is the magnitude and direction of $F_{\text{on A by B}}$?



A 69 N downwards

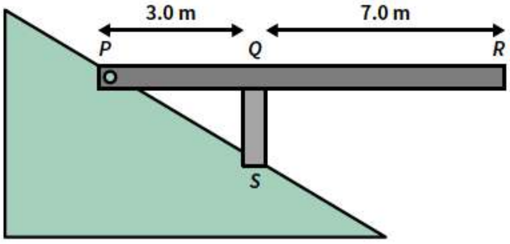
B 49 N downwards

C 69 N upwards

D 49 N upwards

Question 5

A 3000 kg, uniform concrete beam *PR* of length 10.0 m is supported by column *QS*. It is attached at *P* with a frictionless pivot to a stable rock slab.



The magnitude of the force on *QS* by *PR* is:

A 17 640 N

B 19 600 N

C 29 400 N

D 49 000 N

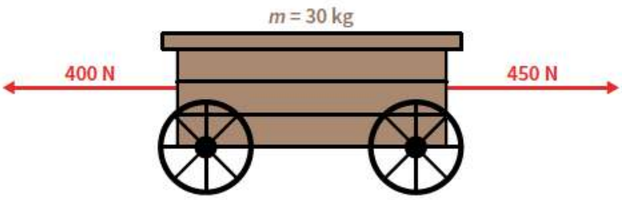
SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (4 MARKS)

A 30 kg cart is being pulled in opposite directions as it moves along a horizontal surface as shown in the diagram. A rope pulls the cart to the right with a force 450 N, while a second rope pulls the cart with a force of 400 N in the opposite direction.



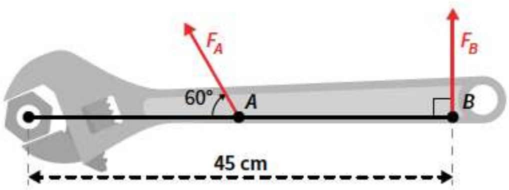
a Calculate the magnitude and direction of the force due to gravity on the cart. (1 MARK)

b Calculate the magnitude of the normal force acting on the cart. (1 MARK)

c Determine the magnitude and direction of the cart's acceleration. (2 MARKS)

Question 7 (3 MARKS)

Albert and Benedict are taking turns turning a rather stiff bolt. Albert thinks an effective method of turning the bolt is by providing a 1000 N halfway along the wrench at an angle of 60° as shown in the diagram. However, Benedict seems to be achieving similar results with a much smaller force at the end of the wrench as shown.



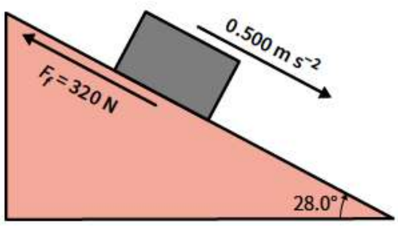
Given that the wrench is 45 cm long and Albert provides F_A at 60°, calculate the force that Benedict is providing to produce the same turning effect. The mass of the wrench can be ignored.

Question 8 (2 MARKS)

Egan is riding a bike along a flat stretch of road but finds that unless he keeps pedaling he will eventually stop moving. Use Newton's First Law to explain why there must be a force acting on Egan even when he stops pedaling.

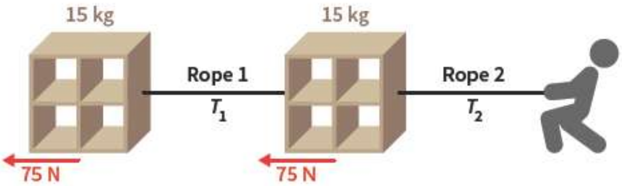
Question 9 (3 MARKS)

A block is sliding down a 28.0° slope whilst accelerating at a rate of 0.500 m s^{-2}. It experiences a frictional force of 320 N resisting its motion. Calculate the normal force acting on the block to the nearest newton.



Question 10 (5 MARKS)

Kaisha is pulling two identical storage units to the right. Each has a mass of 15 kg. A friction force is resisting the motion of each storage unit with a magnitude of 75 N.



a What force would Kaisha have to provide (T_2) in order to maintain a constant speed when she is pulling the storage units around the house? (1 MARK)

b Calculate the tension required in rope 1 to maintain an acceleration of 0.30 m s^{-2}. (2 MARKS)

c Calculate the tension required in rope 2 to maintain an acceleration of 0.30 m s^{-2}. (2 MARKS)

Question 11 (2 MARKS)

A fern with a mass of 8.0 kg is suspended from the roof by two ropes that are at an angle of 55° from the horizontal, as shown in the diagram. Calculate the magnitude of the tension in ropes 1 and 2.

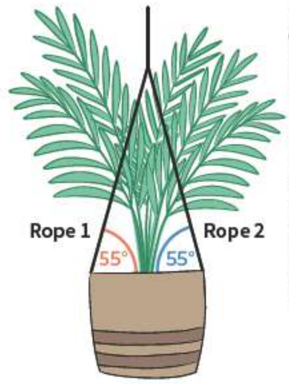
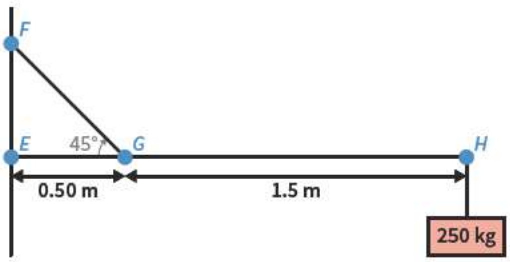


Image: Ekaterina Shabalina/Shutterstock.com

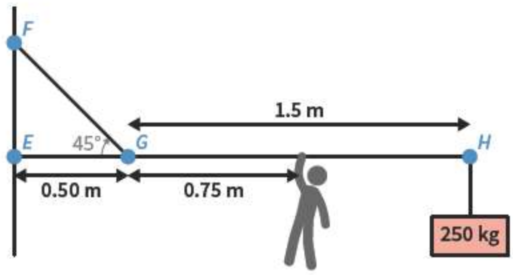
Question 12 (6 MARKS)

A 250 kg mass is hanging from a 2.0 m beam supported by a cable *FG* and attached to a frictionless pivot at *E* such that the system is in static equilibrium. The beam has a mass of 20 kg. The cable makes an angle of 45° to the horizontal.



a Calculate the tension in the cable *FG*. (3 MARKS)

b Agent 007, Jimmy Oath, climbs up the building and grabs on to the beam 0.75 m to the right of point *G*. The cable *FG* has a maximum tensile capacity of 2.0×10^4 N. Determine the maximum mass Jimmy Oath could have such that the cable does not snap. (3 MARKS)



UNIT 2 AOS 1, CHAPTER 10

Conservation of momentum and energy

10

Key knowledge

- apply concepts of momentum to linear motion: $p = mv$
- explain changes in momentum as being caused by a net force: $F_{net} = \frac{\Delta p}{\Delta t}$
- apply the concept of work done by a constant force using:
  - work done = constant force × distance moved in direction of force: $W = Fs$
  - work done = area under force-distance graph
- investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -k\Delta x$
- analyse and model mechanical energy transfers and transformations using energy conservation:
  - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
  - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
  - kinetic energy: $E_k = \frac{1}{2}mv^2$
- analyse rate of energy transfer using power: $P = \frac{E}{t}$
- calculate the efficiency of an energy transfer system: $\eta = \frac{useful\ energy\ out}{total\ energy\ in}$
- analyse impulse (momentum transfer) in an isolated system (for collisions between objects moving in a straight line): $I = \Delta p$
- investigate and analyse theoretically and practically momentum conservation in one dimension.

Image: Tinny Photo/Shutterstock.com

10A MOMENTUM AND IMPULSE

Why is it that a heavy truck is much harder to stop than a car moving at the same speed?
Why is an airbag so effective at preventing fatal motor vehicle injuries?

This lesson will look at the concepts of momentum and impulse, and explore how they apply to collisions between objects in straight lines.

10A Momentum and impulse	10B Work and kinetic energy	10C Gravitational potential energy	10D Springs

Study design dot points

- apply concepts of momentum to linear motion: $p = mv$
- explain changes in momentum as being caused by a net force: $F_{net} = \frac{\Delta p}{\Delta t}$
- analyse impulse (momentum transfer) in an isolated system (for collisions between objects moving in a straight line): $I = \Delta p$
- investigate and analyse theoretically and practically momentum conservation in one dimension

Key knowledge units

Momentum	2.1.4.1 & 2.1.18.1
Impulse	2.1.5.1 & 2.1.17.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas for this lesson	$p = mv$ momentum
	$\Sigma p_i = \Sigma p_f$ conservation of momentum
	$I = \Delta p = m\Delta v$ impulse
	$I = F\Delta t$ impulse

Definitions for this lesson

collision the coming together of two or more objects where each object exerts a force on the other

impulse the change in momentum of a body as the result of a force acting over a time (vector)

isolated system a collection of interacting objects for which there is no external exchange of mass and energy

momentum a quantity of a body in motion which is equal to the mass of the body multiplied by its velocity (vector)

Momentum 2.1.4.1 & 2.1.18.1

OVERVIEW

Momentum, p, is a vector quantity measured in both kg m s^{-1} and N s. The law of conservation of momentum states that the total momentum before a collision will be equal to the total momentum after the collision in all isolated systems, $\Sigma p_i = \Sigma p_f$.

THEORY DETAILS

Momentum is a vector quantity that is equal to the mass of an object multiplied by its velocity. It has units of kg m s^{-1} or N s and is in the same direction as velocity.

[redacted]

$p = mv$

p = momentum (N s or kg m s^{-1}), m = mass (kg), v = velocity (m s^{-1})

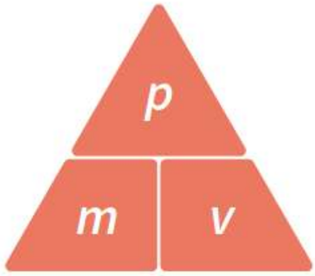


Figure 1 Formula triangle for momentum

An object with a greater momentum will require a greater force and/or a greater time to stop. Consider a heavy truck moving at the same speed as a small car. Due to its mass, the truck has a much greater momentum and, as a result, will take a greater distance and time to stop when compared to a car if they apply the same braking force.

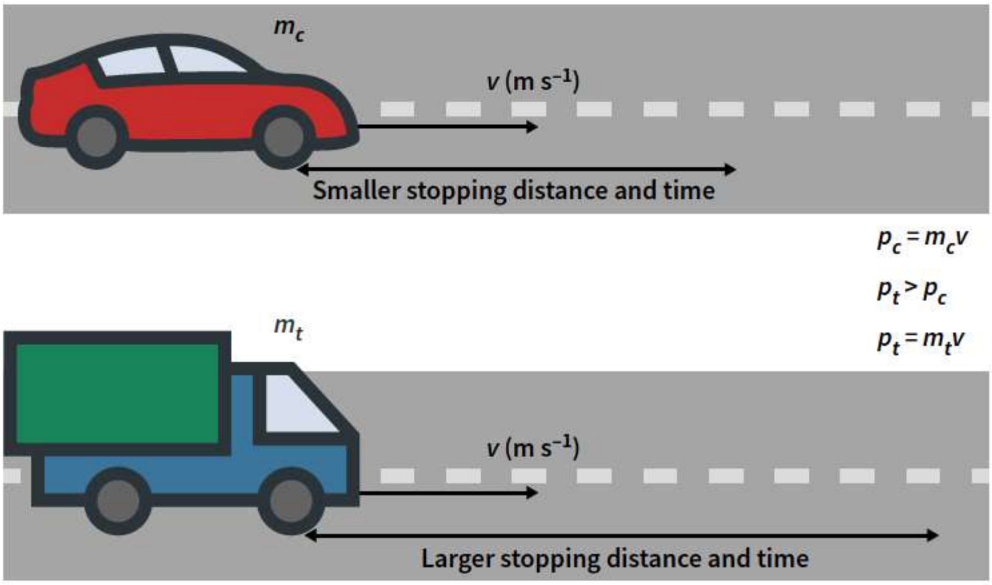


Image: IhorZigor/Shutterstock.com

Figure 2 Comparison of the momentum and stopping distances of a car and truck moving at the same velocity to illustrate the truck's greater momentum.

Worked example 1

A car with a mass of 2000 kg is travelling east at 25 m s^{-1}. Determine the momentum of the car.

Working	Process of thinking
$p = mv = 2000 \times 25 = 5.0 \times 10^4$ kg m s^{-1} or N s	As we know the mass and velocity of the car, we will use $p = mv$ to solve for momentum. $m = 2000$ kg, $v = 25$ m s^{-1} east
The momentum of the car is 5.0×10^4 kg m s^{-1} or N s to the east.	Remember to include a magnitude and direction as momentum is a vector quantity.

Conservation of momentum

The law of conservation of momentum states that the total momentum of an isolated system will not change during any interaction or collision, such that the total initial momentum, Σp_i, will be equal to the total final momentum, Σp_f.

In VCE Physics, it is assumed that all calculation questions involving momentum will occur in an isolated system where momentum is conserved.

$\Sigma p_i = \Sigma p_f$

Σp_i = total initial momentum (N s or kg m s^{-1}), Σp_f = total final momentum (N s or kg m s^{-1})

In this context, Σ means 'the sum of' to indicate that we calculate the sum of all of the individual momenta of the objects in an isolated system.

The law of conservation of momentum applies to any isolated system. Some examples can be seen in Figure 3, where the arrows represent momentum. The same process of calculations used in Worked Example 2 can be used to analyse the motion of all collisions, ensuring that the vector properties (magnitude and direction) of momentum are considered.

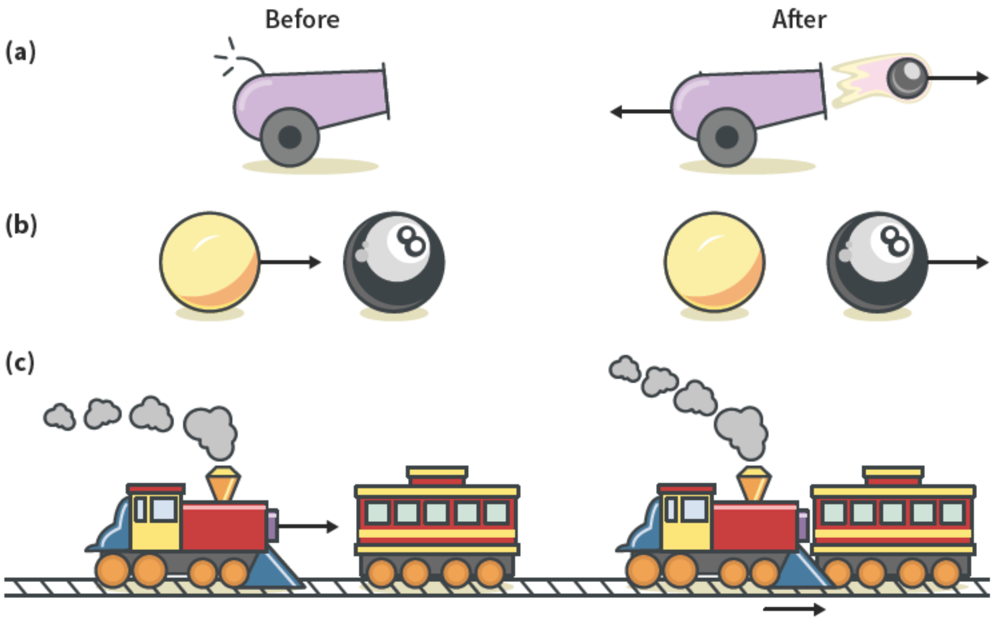


Figure 3 **(a)** When a stationary cannon fires a cannonball, the forward momentum of the cannonball is balanced by the backwards momentum of the cannon so the total momentum remains zero. **(b)** When a cue ball is stationary after a collision, the eight ball will have a momentum equal to the cue ball's initial momentum. **(c)** When a train engine makes contact and sticks to a stationary train carriage, we consider them a combined mass that will have a reduced speed but a momentum equal to that of the engine before the collision.

Worked example 2

During a golf tournament, Wiger Toods uses his golf club to strike a stationary golf ball with a mass of 0.020 kg. The mass of his golf club is 0.250 kg and it travels at 40.0 m s^{-1} immediately before the collision and it slows during the collision so that it travels at 30.0 m s^{-1} immediately after the collision. Assume the golf club and the ball are an isolated system during the collision.

a **Determine the magnitude of the total momentum of the system before the golf club contacts the ball.**

b **What is the magnitude of the momentum of the club-ball system after the ball has been struck?**

c **Calculate the speed of the golf ball immediately after it has made contact with the club.**

	Working	Process of thinking
a	$\Sigma p_i = m_{club} u_{club} = 0.250 \times 40.0 = 10.0$ kg m s^{-1} or N s The initial momentum of the system is 10.0 kg m s^{-1} or N s.	$m_{club} = 0.250$ kg, $u_{club} = 40.0$ m s^{-1} Tip: we use u to represent the initial velocity and v for the final velocity.
b	$\Sigma p_i = \Sigma p_f$ $\Sigma p_f = 10.0$ kg m s^{-1} or N s	As we do not know the velocity of the ball after it has been struck, we need to use the law of conservation of momentum: $\Sigma p_i = \Sigma p_f$.
c	$\Sigma p_f = 10.0$ kg m s^{-1} or N s	We know the final momentum of the system is 10.0 kg m s^{-1} or N s.
	$\Sigma p_f = p_{ball} + p_{club}$ $\Sigma p_f = m_{ball} v_{ball} + m_{club} v_{club}$	We also know the final momentum will be equal to the sum of the momenta of the ball and club, $\Sigma p_f = p_{ball} + p_{club}$. Convert the masses to kg.
	$\therefore 10.0 = 0.020 \times v_{ball} + 0.250 \times 30.0$	$m_{ball} = 0.020$ kg, $m_{club} = 0.250$ kg, $v_{club} = 30.0$ m s^{-1}, $v_{ball} = ?$ m s^{-1}
	$v_{ball} = 125 = 1.3 \times 10^2$ m s^{-1}	Rearrange for the speed of the ball: $v_{ball} = \frac{10.0 - (0.250 \times 30.0)}{0.020}$

For conservation of momentum questions, it is important to treat momentum as a vector quantity with both magnitude and direction. At the start of a question, define what direction is considered positive. Any velocities or momenta in the opposite direction should be considered negative.

Worked example 3

During a game of NFL, two players that each have a mass of 100 kg are running towards each other. The first player is running at a speed of 3.0 m s^{-1} to the right and the second player is running to the left at a speed of 4.0 m s^{-1}.

Determine the magnitude and direction of the total momentum of the two player system.

Working	Process of thinking
$\Sigma p = p_1 + p_2 = mv_1 + mv_2$	The total momentum will be the sum of the two players' individual momenta: $\Sigma p = p_1 + p_2$
	Take the right as positive, therefore the velocity of the second player is considered to be negative.
$\Sigma p = 100 \times 3.0 + 100 \times (-4.0)$	$m = 100$ kg, $v_1 = 3.0$ m s^{-1}, $v_2 = -4.0$ m s^{-1}
$\Sigma p = -1.0 \times 10^2$ kg m s^{-1} or N s	
$\Sigma p = 1.0 \times 10^2$ kg m s^{-1} or N s to the left	Remember that momentum is a vector quantity, so a negative value in this example indicates to the left.

Impulse 2.1.5.1 & 2.1.17.1

OVERVIEW

A force, F, acting on an object over a period of time, t, causes a change in momentum, Δp, of that object. This change in momentum is equal to the impulse, I, on that object. The impulse experienced by an object will be in the same direction as this force and change in momentum. Impulse has the units of kg m s^{-1} and N s.

THEORY DETAILS

When a body changes its velocity (speed or direction), which happens whenever two bodies collide, there are forces that act to accelerate and change the velocity of those bodies. If we consider a ball being struck by a bat as in Figure 4, there will be a force which acts to accelerate the ball. According to Newton's Third Law, there will also be an equal and opposite force that acts to accelerate the bat.

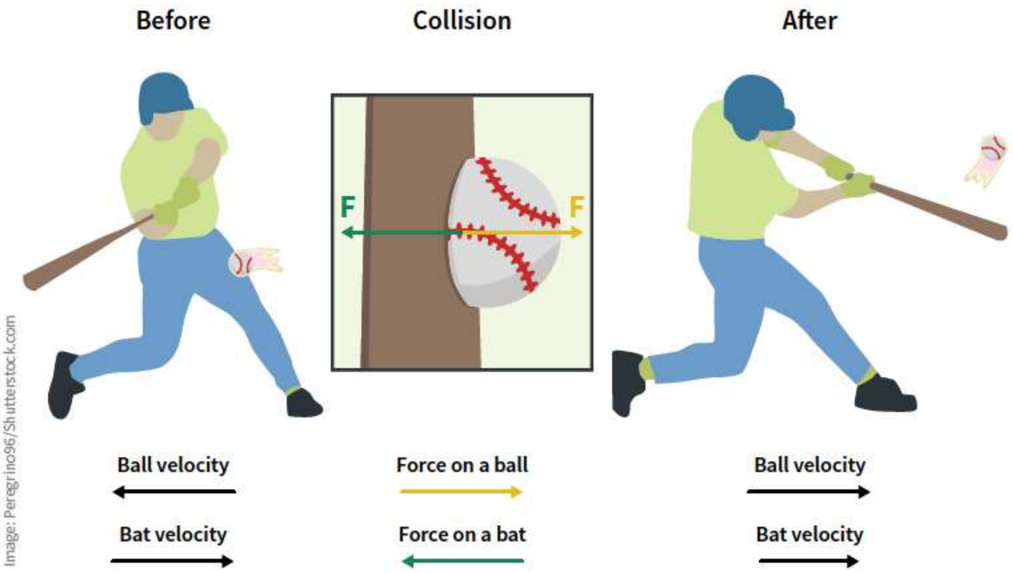


Image: Peregrino96/Shutterstock.com

Figure 4 The change in velocity, and therefore momentum, of an object is due to a net force acting on that object. A force on the ball by the bat acts to the right, which causes a change in velocity and momentum to the right.

We can use the equation for momentum, $p = mv$, to deduce that the net force, F_{net}, acting to change the velocity of a body causes a change in the momentum, Δp, of the body.

From $F_{net} = ma$ and $a = \frac{\Delta v}{\Delta t}$, we can derive an alternative equation for the net force acting on a body.

$$F_{net} = m \times \frac{\Delta v}{\Delta t} = \frac{m \times \Delta v}{\Delta t}$$

As $\Delta p = m \times \Delta v$, we conclude $F_{net} = \frac{\Delta p}{\Delta t}$.

This equation shows how the net force experienced by a body, and the time over which the force acts, affects the change in momentum of the body. Consider two cars of the same mass which are having a drag race.

- If one car accelerates to 100 km h^{-1} in the same time that the other car accelerates to 50 km h^{-1}, it has experienced a greater change in momentum and hence a greater net force.
- Similarly, if both cars accelerate to 100 km h^{-1} at different rates, the change in momentum will be the same but the car that took a greater time must have experienced a smaller net force.

The change in momentum of an object is known as impulse, I. Hence impulse has the same units as momentum, kg m s^{-1} or N s.

We can rearrange our previous equation to make the change in momentum (impulse) the subject.

> $$I = F\Delta t$$
> **I = impulse (N s or kg m s^{-1}), F = force (N), Δt = change in time (s)**

The direction of the impulse (change in momentum) is always in the **same direction as the force applied**.

- If the force varies during the collision, then F represents the average force, F_{avg}.
- When calculating impulse with a force and a time, it is more common to use newton-seconds (N s) than to use kilogram meters per second (kg m s^{-1}).

> $$I = \Delta p = m\Delta v$$
> **I = impulse (N s or kg m s^{-1}), Δp = change in momentum (N s or kg m s^{-1}), m = mass (kg), v = velocity (m s^{-1})**

The direction of the impulse (change in momentum) is always in the **same direction as the change in momentum and the change in velocity**.

With an understanding of impulse being the change in momentum caused by a force acting over a period of time, we can interpret collisions and the conservation of momentum using Newton's third law.

Consider two balls, A and B, which collide as per Figure 5. There is a force on ball A by ball B acting to the left, and there is also a force on B by A which is equal in magnitude but opposite in direction: $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$.

- Knowing that $I = F\Delta t$ and that the time of the collision is the same for both balls, it can be inferred that ball A gives ball B impulse to the right and ball B gives ball A an equal magnitude of impulse to the left.
- Knowing that impulse is the change in momentum, we can conclude that $\Delta p_A = -\Delta p_B$ and momentum is conserved.

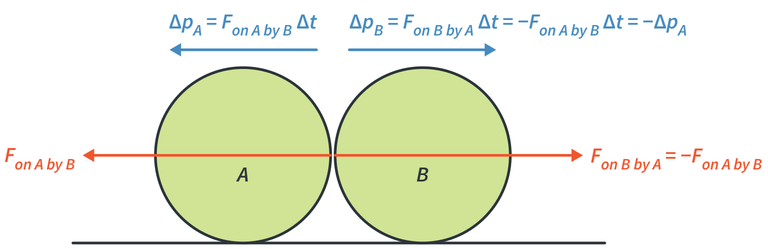


Figure 5 Each ball gives the other impulse (change in momentum) with equal magnitude in the opposite direction which means the total momentum is conserved.

Worked example 4

During the 2020 NFL Superb Cup, a punter strikes a stationary football of mass 0.425 kg. The football leaves the punter's foot with a speed of 30 m s^{-1} to the north, and was in contact with their foot for 15.0×10^{-3} s.

a **Determine the change in momentum of the football.**

b **Calculate the impulse given to the football.**

c **Calculate the impulse given to the punter's foot.**

d **Determine the average force experienced by the football during its contact with the punter's foot.**

Working	Process of thinking
a $\Delta p_{ball} = m_{ball}\Delta v_{ball} = m \times (v - u) = 0.425 \times (30 - 0)$ $\Delta p_{ball} = 12.75 = 12.8$ kg m s^{-1} or N s to the north	$m_{ball} = 0.425$ kg, $v_{ball} = 30$ m s^{-1} north Remember that momentum is a vector quantity and requires a magnitude and a direction.
b $I_{ball} = \Delta p_{ball} = 12.8$ kg m s^{-1} or N s to the north	Impulse is equal to change in momentum: $I_{ball} = \Delta p_{ball}$. Impulse is a vector so it must include a direction.
c $I_{foot} = -I_{ball} = 12.8$ kg m s^{-1} or N s to the south	The impulse given to the punter's foot will be equal in magnitude and opposite in direction to the impulse given to the football: $I_{foot} = -I_{ball}$. The opposite direction to north is south.
d $I_{foot} = F_{avg}\Delta t$	As we are looking for the average force, we will use to equation $I = F_{avg}\Delta t$.
$12.75 = F_{avg} \times 15.0 \times 10^{-3}$	$t = 15.0 \times 10^{-3}$ s, $I_{ball} = 12.75$ kg m s^{-1} or N s to the north
$F_{avg} = 850$ N to the north	Force is a vector so it must include a direction.

Impulse in collision safety

Consider the airbag in a car during a car crash. An airbag acts to extend the time of impact and stops the head abruptly stopping as it hits the steering wheel, meaning the momentum of the driver's head will decrease to zero over a longer duration.

Knowing that $I = F\Delta t$, we can rearrange this to find $F = \frac{I}{\Delta t}$. As the airbag acts to increase Δt, the force experienced by the driver's head will be greatly reduced compared to if there was no airbag. Decreasing the impact force by increasing the time over which momentum changes is also the principle behind seat belts, helmets, crumple zones, brakes, parachutes, and many other types of safety equipment.

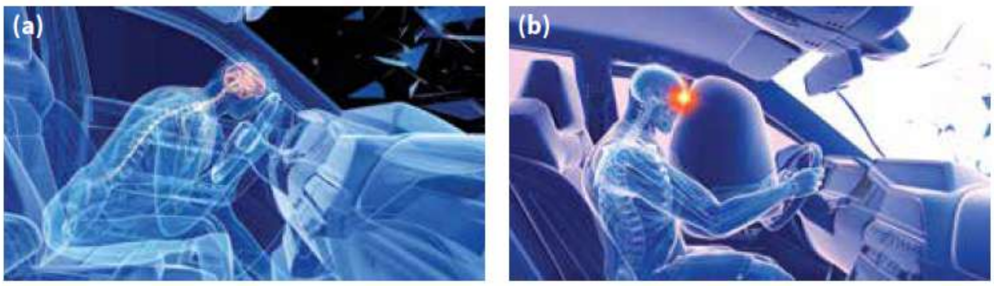
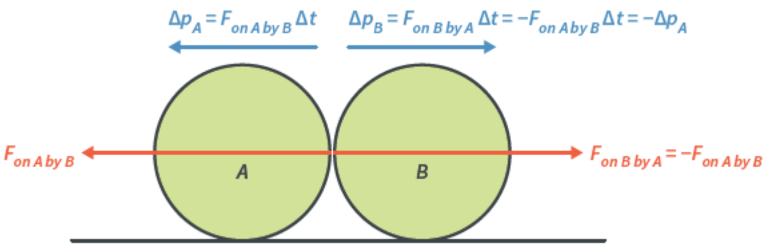


Image: SciePro/Shutterstock.com Image: SciePro/Shutterstock.com

Figure 6 **(a)** A car crash without an airbag will result in a large force on the driver as the impulse occurs over a short duration. **(b)** An airbag acts to slow the collision and reduce the amount of force experienced by the driver.

Theory summary

- **Momentum** is a vector quantity that is the product of the velocity and the mass of an object measured in kg m s^{-1} or N s.
  - $p = mv$
- The law of **conservation of momentum** states that the total momentum before a collision will be equal to the total momentum after the collision within an isolated system.
  - $\Sigma p_i = \Sigma p_f$
- When an object experiences a change in momentum it is due to a net force acting on the object.
  - $F_{net} = \frac{\Delta p}{\Delta t}$
- The change in momentum of an object is called **impulse**.
  - $I = F\Delta t$
  - $I = \Delta p = m\Delta v$
  - Impulse has the same direction as Δp and F_{net}
  - Impulse is measured in kg m s^{-1} or N s
- The impulse (change in momentum) experienced by two objects in a collision will always be equal in magnitude and opposite in direction.



KEEN TO INVESTIGATE?

PhET 'Collision Lab' simulation
phet.colorado.edu/en/simulation/collision-lab

YouTube video: WA O – Crumple zones and impulse
youtu.be/bO8E6j16L0A

CONCEPT DISCUSSION QUESTION

Alex falls head first off his bicycle and onto the road. Thankfully, Alex was wearing a helmet and did not get injured. For each of the following variations on this situation, discuss how the force, time, impulse, and change in momentum would vary:

a when Alex is not wearing a helmet.

b when Alex is wearing a normal bicycle helmet.

c when Alex is wearing a helmet made of concrete.

Answers on page 508

Hints

How do the initial and final velocities vary in each situation?

How does change in momentum relate to impulse?

What is the relationship between impulse, force, and time?

How does the time of a collision affect the force experienced by the body?

[redacted]

10A Questions

THEORY REVIEW QUESTIONS

Question 1

Momentum is a _________ (vector/scalar) quantity equal to the multiplication of mass and (acceleration/velocity).

The direction of impulse is the _________ (opposite/same) as the direction of the change in momentum and is caused by _________ (a net force acting on/a change in displacement of) the mass.

Use the following information to answer Questions 2–4.

Two cars of equal mass are approaching an intersection when the light turns red. Car *A* decelerates to 0 m s^{-1} in a very short time, whereas car *B* slowly decelerates to 0 m s^{-1} over a long time.

Question 2

The magnitude of the change in momentum of car *B* is _________ (less than/the same as/greater than) the change in momentum of car *A*.

Question 3

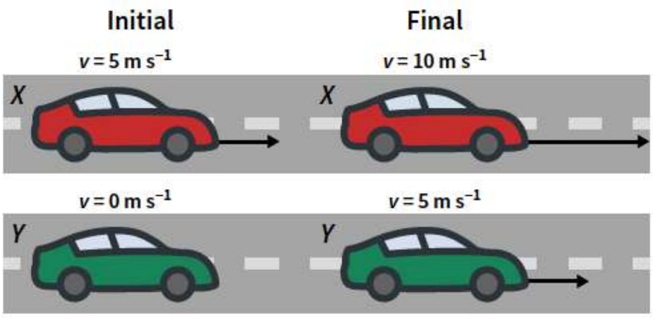
The magnitude of the impulse experience by car *B* is _________ (less than/the same as/greater than) the impulse given to car *A*.

Question 4

The magnitude of the force acting to decelerate car *B* is _________ (less than/the same as/greater than) the force acting to decelerate car *A*.

Question 5

Two cars, *X* and *Y*, of the same mass are on a road. Car *X* has an initial velocity of 5 m s^{-1} to the right and car *Y* is initially stationary. After a given amount of time, car *X* and *Y* have velocities of 10 m s^{-1} and 5 m s^{-1} respectively to the right.

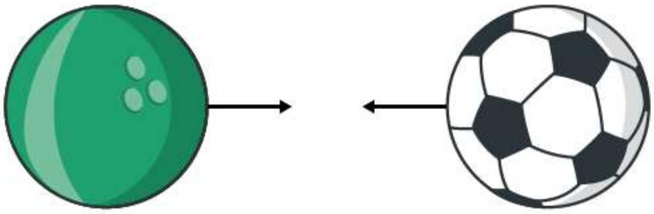


Which of the following options best compares the initial momentum and final momentum of car *X* and *Y*, as well as the impulse they experience?

	Initial momentum	Impulse	Final momentum
A	$p_X > p_Y$	$I_X > I_Y$	The same
B	The same	$I_Y > I_X$	$p_Y > p_X$
C	$p_X > p_Y$	The same	$p_X > p_Y$

Use the following information to answer Questions 6 and 7.

A bowling ball and a soccer ball are rolling towards each other and collide. The bowling ball has a greater mass than the soccer ball. The impulse given to the soccer ball is known to be equal to 10 N s to the right.



Question 6

The impulse given to the bowling ball is _________ (lesser/greater/equal) in magnitude compared to the impulse given to the soccer ball and acts towards the _________ (right/left).

Question 7

What is the change in momentum of the bowling ball?

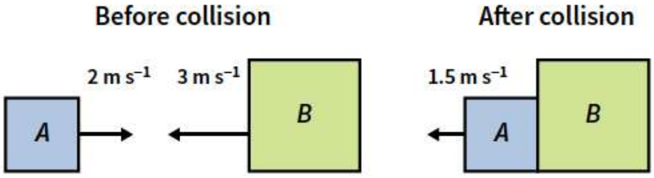
A 10 kg m s^{-1}

B 10 kg m s^{-1} to the right

C 10 kg m s^{-1} to the left

Question 8

Block *A*, of mass m_A, is travelling to the right at a speed of 2 m s^{-1} and collides with block *B*, of mass m_B, which is travelling to the left at 3 m s^{-1}. After the collision blocks *A* and *B* are moving to the left at a speed of 1.5 m s^{-1}.



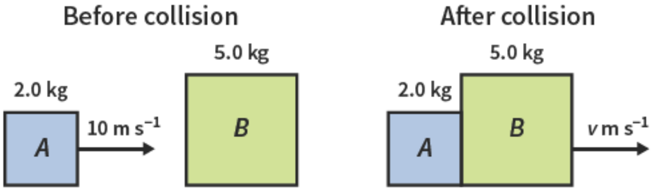
Which of the following options correctly indicates an equation for the momentum of the two blocks before the collision, and the momentum of the combined blocks after the collision. Take right as the positive direction.

	Momentum of block *A* before the collision	Momentum of block *B* before the collision	Momentum of block *A* and *B* after the collision
A	$p_A = m_A \times 2$	$p_B = m_B \times (-3)$	$\Sigma p_{after} = (m_A + m_B) \times 1.5$
B	$p_A = m_A \times 2$	$p_B = m_B \times (-3)$	$\Sigma p_{after} = (m_A + m_B) \times (-1.5)$
C	$p_A = m_A \times (-2)$	$p_B = m_B \times 3$	$\Sigma p_{after} = (m_A + m_B) \times (-1.5)$
D	$p_A = m_A \times 2$	$p_B = m_B \times 3$	$\Sigma p_{after} = (m_A + m_B) \times 1.5$

DECONSTRUCTED EXAM-STYLE QUESTION

Question 9 (6 MARKS)

Block *A* of mass 2.0 kg is moving to the right at a speed of 10 m s^{-1}. It then collides and sticks to block *B* of mass 5.0 kg. The force during the collision acts over 4.0×10^{-2} s.



Prompts

a Which of the following shows the momentum of block *A* before the collision.

- **A** 0 kg m s^{-1}
- **B** 5.0 kg m s^{-1} to the right
- **C** 10 kg m s^{-1} to the right
- **D** 20 kg m s^{-1} to the right

b Which of the following shows the momentum of block *B* before the collision?

- **A** 0 kg m s^{-1}
- **B** 5.0 kg m s^{-1} to the right
- **C** 10 kg m s^{-1} to the right
- **D** 20 kg m s^{-1} to the right

c Which of the following is the total momentum after the collision?

- **A** 0 kg m s^{-1}
- **B** 5.0 kg m s^{-1} to the right
- **C** 10 kg m s^{-1} to the right
- **D** 20 kg m s^{-1} to the right

d Which of the following options is the velocity, *v* m s^{-1}, of the two blocks after the collision?

- **A** 10 m s^{-1} to the right
- **B** 4.0 m s^{-1} to the right
- **C** 2.9 m s^{-1} to the right
- **D** 1.4 m s^{-1} to the right

e Which of the following options is the change in momentum of block *B*?

- **A** 50 kg m s^{-1} to the left
- **B** 14 kg m s^{-1} to the right
- **C** 20 kg m s^{-1} to the left
- **D** 8.0 kg m s^{-1} to the right

Question

f Determine the magnitude of the average force experienced by block *B* when it collides with block *A*. (6 MARKS)

EXAM-STYLE QUESTIONS

This lesson

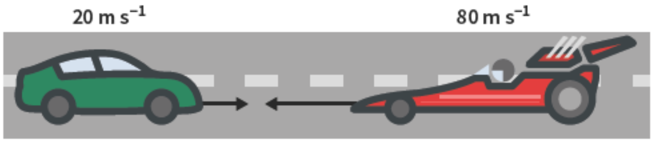
Question 10 (2 MARKS)

A bird of mass 3.5 kg is migrating south at a speed of 10 m s^{-1}. What is the momentum of the bird?

Question 11 (4 MARKS)

During the Melbourne grand prix, a car accidentally enters the track and has a head on collision with an F1 car. The car of mass 1900 kg was travelling at 20 m s^{-1} to the right and the F1 car of mass 750 kg was travelling at 80 m s^{-1} to the left. After the collision, the two cars stick together. Assume the two cars are an isolated system.

Before collision



After collision

a Calculate the total momentum of the system. (2 MARKS)

b Calculate the final velocity, *v* m s^{-1}, of the two cars immediately after the collision. (2 MARKS)

Question 12 (7 MARKS)

A truck of mass 10 000 kg is travelling along an outback highway at a speed of 25 m s^{-1}. A camel walks onto the road and the truck is forced to stop with an average breaking force of 12 500 N.

a Show that the magnitude of the impulse experienced by the truck is 2.5×10^5 kg m s^{-1}. (1 MARK)

b Calculate how long the truck took to come to rest. (2 MARKS)

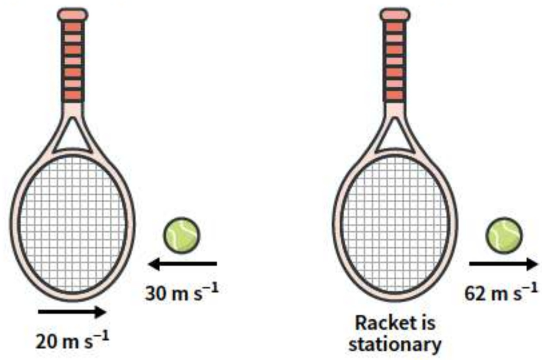
c Calculate the magnitudes of both the initial and final momentum of the truck. (2 MARKS)

d Is momentum conserved in this situation? Explain your answer. (2 MARKS)

Question 13 (8 MARKS)

A young tennis player is frustrated as to why he is unable to hit the ball as hard as his opponents. Instead of trying to improve his game, he intends to use his physics knowledge to analyse his shots. He compiles the following data.

Mass of tennis ball	0.050 kg
Mass of tennis racket	0.230 kg
Speed of tennis ball before being struck	30 m s^{-1} (towards the racket)
Speed of tennis ball after being struck	62 m s^{-1} (away from the racket)
Speed of tennis racket before striking the ball	20 m s^{-1}
Average force on the tennis ball by the racket	230 N



a Calculate the magnitude of the impulse given to the tennis ball by the racket. Include an appropriate unit in your answer. (2 MARKS)

b What is the magnitude and direction (according to the diagram) of the impulse given to the racket by the tennis ball? (2 MARKS)

c Calculate the time that the tennis ball is in contact with the racket. (2 MARKS)

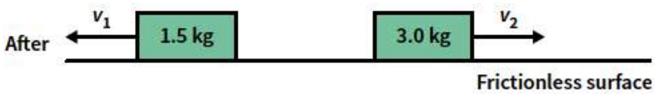
d What is the magnitude and direction (according to the diagram) of the force acting on the tennis racket? (2 MARKS)

Adapted from 2019 NHT VCAA Exam Section B Q7

Question 14 (3 MARKS)

A 1.5 kg block is initially moving towards the right at a speed of u_1 on a frictionless surface towards a stationary block of mass 3.0 kg.

After the collision, the 1.5 kg block is moving the the left at a speed of v_1 and the 3.0 kg block is moving towards the right at a speed of v_2.



The 3.0 kg block has a greater momentum after the collision than the 1.5 kg block did before the collision.

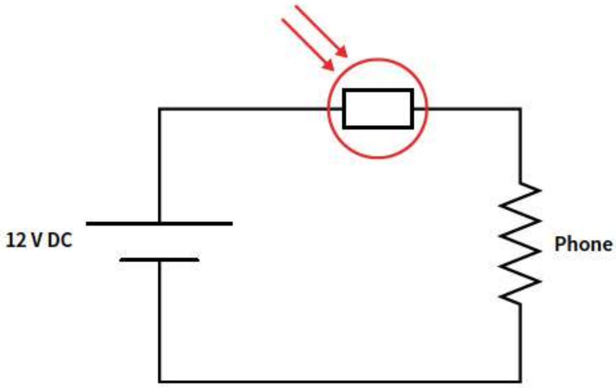
Explain why the greater momentum of the 3.0 kg block after the collision is consistent with the law of conservation of momentum.

Adapted from 2012 VCAA Exam 1 Section A AoS 1 Q2

Previous lessons

Question 15 (5 MARKS)

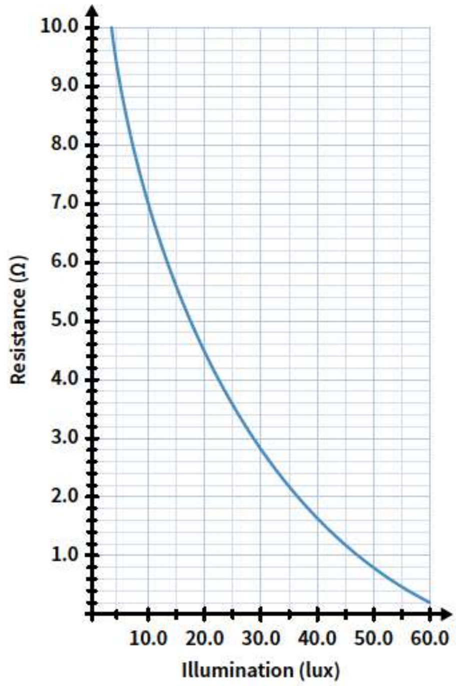
A young electrical engineer, Matt Amatix, is attempting to create a circuit that automatically charges his phone when the sunlight entering his room is at a certain level. He constructs a circuit with a light dependent resistor as shown in the diagram. The phone charges correctly when there is a voltage drop of exactly 5.0 V across it. The phone has a resistance of 4.0 Ω. The DC power supply provides 12 V.



a What is the current flowing through the circuit when the charger operates correctly? (1 MARK)

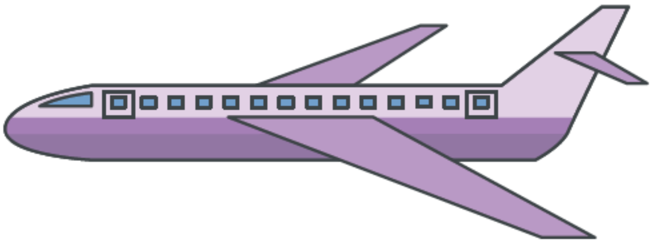
b Determine the resistance of the light dependent resistor for the phone charger to correctly operate. (3 MARKS)

c At what luminosity will the phone charger correctly operate? (1 MARK)



Question 16 (9 MARKS)

A plane and all of its cargo has a mass of 530 tonnes. The wings produce a lift force, F_L, of 5.60×10^6 N acting vertically upwards. Take the acceleration due to gravity to be 9.80 m s^{-2}.



a What is the magnitude and direction of the force due to gravity acting on the plane. (2 MARKS)

b On the included diagram of the plane, draw and label a force vector representing the force due to gravity. (2 MARKS)

c On the same diagram, draw and label a force vector representing the lift force. (2 MARKS)

d Determine the magnitude of the acceleration of the plane in the vertical direction. (3 MARKS)

Key science skills

Question 17 (8 MARKS)

A physics teacher decides that her students are not well enough prepared for the key science skills section of their exam and sets them a surprise quiz on a Friday afternoon. One question presents the students with a toy car of mass 1 kg, that collides and sticks to a second stationary toy car. Information about the initial velocity of the first toy car and the velocity of the combined toy cars after the collision is given. It is known that there is an uncertainty in the combined velocity after the collision of ± 0.25 m s^{-1}.

Initial velocity of first toy car before collision, u (m s^{-1})	**Velocity of combined toy cars after collision, v (m s^{-1})**
2.0	0.66
4.0	1.45
6.0	1.80
8.0	2.70
10.0	3.30

a On a set of axes, plot the data for momentum on the vertical axis and velocity on the horizontal axis. Include the following:

- An appropriate scale
- Axis labels with units
- Uncertainty bars
- A line of best fit

(5 MARKS)

b Knowing that the conservation of momentum leads to $m_1 \times u = (m_1 + m_2) \times v$, use the gradient of the line of best fit to determine the mass of the second toy car. (3 MARKS)

10B WORK AND KINETIC ENERGY

In Chapter 2, we looked at energy at the scale of atoms and molecules. Now we will examine its role at the scale of everyday objects and how it assists us in describing various types of motion. This lesson will cover kinetic energy, work and power.

10A Momentum and impulse	10B Work and kinetic energy	10C Gravitational potential energy	10D Springs

Study design dot points

- Apply the concept of work done by a constant force using:
  - work done = constant force × distance moved in direction of force: $W = Fs$
  - work done = area under force-distance graph
- analyse and model mechanical energy transfers and transformations using energy conservation:
  - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
  - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
  - kinetic energy: $E_k = \frac{1}{2}mv^2$
- analyse rate of energy transfer using power: $P = \frac{E}{t}$
- calculate the efficiency of an energy transfer system: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$

Key knowledge units

Kinetic energy	2.1.14.3
Work	2.1.12.1
Power	2.1.15.1
Energy efficiency	2.1.16.1

Formulas for this lesson

Previous lessons		New formulas
2D	$W = Fs$	$KE = \frac{1}{2}mv^2$ kinetic energy
4A	$P = \frac{E}{t}$	$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$ efficiency

Definitions for this lesson

work the change in energy caused by a force displacing an object in the direction it is acting in

Kinetic energy 2.1.14.3

OVERVIEW

Kinetic energy is the energy an object has because it is in motion. The kinetic energy of an object can be calculated by $KE = \frac{1}{2}mv^2$.

THEORY DETAILS

The energy that is related to the motion of an object is called **kinetic energy**. Lesson 2A looked at the relationship between kinetic energy and the temperature of a system at the level of particles. However, we can also apply this concept to the level of larger objects and systems. On a larger scale, kinetic energy refers to the energy of an object associated with its translational motion.

The amount of kinetic energy that an object has at a given moment depends on its mass and its velocity.

- For two objects that are travelling at the same velocity, the object with a larger mass will have more kinetic energy.
- For two objects with the same mass, the object with a larger velocity will have more kinetic energy.

This helps to explain why we might say that a truck that is travelling at 100 km h^{-1} (more mass and faster) would have more kinetic energy than a bike travelling at 10 km h^{-1} (less mass and slower).

$$KE = \frac{1}{2}mv^2$$

KE = kinetic energy (J), m = mass (kg), v = velocity (m s^{-1})

- Kinetic energy is always positive.
- Although velocity is a vector quantity, squaring the velocity to calculate kinetic energy means that kinetic energy is a scalar quantity.
- In VCE Physics, it is common to see kinetic energy written as E_K, however in order to clearly differentiate between different types of energy, in this book it will be presented as KE.

For an object of mass m with an initial velocity u and a final velocity v, the change in kinetic energy, ΔKE, is given by:

$$\Delta KE = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2 = \frac{1}{2}m(v^2 - u^2)$$

Whilst the kinetic energy at a particular point in time cannot be negative, the change in kinetic energy can be. This is the case when the magnitude of the final velocity, v, is smaller than the magnitude of the initial velocity, u, for example when the object being considered is slowing down.

When an object starts accelerating from rest, this formula can be simplified to $\Delta KE = \frac{1}{2}mv^2$, as $u = 0$ m s^{-1}.

Worked example 1

Maria is riding her tricycle after school. The total mass of Maria and the tricycle is 60 kg.

a What is the kinetic energy of Maria and the tricycle when riding at 10 m s^{-1}?

b Maria accelerates to 15 m s^{-1}. What is the change in kinetic energy of Maria and the tricycle over this period of acceleration?

Working	Process of thinking
a $KE = \frac{1}{2}mv^2$ $KE = \frac{1}{2} \times 60 \times 10^2 = 3000 = 3.0 \times 10^3$ J	From the question, m = 60 kg and v = 10 m s^{-1}
b $\Delta KE = \frac{1}{2}m(v^2 - u^2)$ $\Delta KE = \frac{1}{2} \times 60 \times (15^2 - 10^2) = 3750 = 3.8 \times 10^3$ J	v = 15 m s^{-1} since it is the final velocity. u = 10 m s^{-1} since it is the initial velocity.

Work 2.1.12.1

OVERVIEW

The energy of an object describes its ability to cause change. Work is done when an applied force causes a change in energy.

THEORY DETAILS

Work is defined as the change in energy of an object arising from an applied force. A force is said to do work on an object when there is a displacement of the object due to the action of the force. If we know the total energy of an object at two different positions, then the work done in order to move the object can be found by subtracting the object's initial energy from the object's final energy.

Whilst we can define the work done as the change in energy of the object, it can also be calculated using the following formula:

> $W = Fs$
>
> **W = work done on an object (J), F = magnitude of the force parallel to motion (N),**
> **s = displacement (m)**

For this lesson we will mainly consider how work is related to changes in kinetic energy. Recall Newton's First Law of Motion, which tells us that when a net force is applied to an object, the object will experience a change in velocity (acceleration) parallel to the direction of the force. From the previous section on kinetic energy, we know that a change in the magnitude of velocity leads to a change in kinetic energy. If no other changes of energy occur, then we can relate work to kinetic energy as follows:

$$W = \Delta KE \;\therefore Fs = \frac{1}{2}m(v^2 - u^2)$$

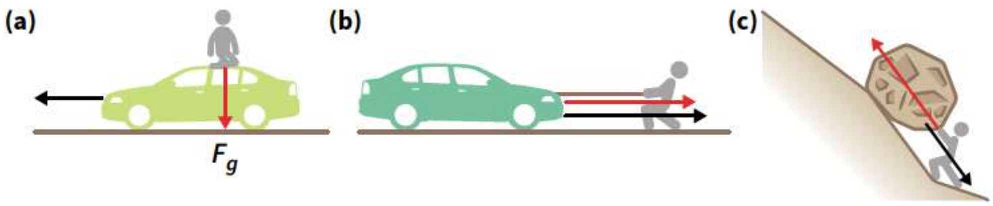


Figure 1 The black arrow represents the direction of displacement and the red arrow the direction of the applied force. **(a)** No work is being done. **(b)** Work is being done on the car by the person. **(c)** Work is being done on the person by the rock.

When an individual force is applied to an object, there are three different outcomes that can occur:

1. The force is applied perpendicular to the direction of motion and causes no change in the magnitude of the velocity (Figure 1(a)).
   - Therefore the change in kinetic energy and work done is zero.
   - We say that no work has been done.
2. The force causes an acceleration in the direction of motion (Figure 1(b)).
   - This will cause the magnitude of velocity to increase and therefore the change in kinetic energy and work done will be positive.
   - This means the object has gained energy, so we say that **work has been done on the object**.
3. The force causes an acceleration opposite to the direction of motion (Figure 1(c)).
   - This will cause the magnitude of velocity to decrease (deceleration) and therefore the change in kinetic energy and work done will be negative.
   - This means the object has lost energy, so we say that **work has been done by the object**.

More than one force can do work on an object at the same time. For example, when you push something along the ground, you are doing positive work (the displacement is in the same direction as your pushing), however the force due to friction with the ground does negative work (the displacement is in the opposite direction to the force). When this is the case, the net work done can be calculated by multiplying the net force by the displacement.

Worked example 2

Josephine's toy car has a mass of 0.40 kg and is rolling along a frictionless floor at 5.0 m s^{-1}. She then applies a force of 5.0 N on the car over a distance of 3.0 m.

a How much work did Josephine do on the car?

b Calculate the final kinetic energy of the car.

Working	Process of thinking
a $W = Fs$ $W = 5.0 \times 3.0 = 15$ J	Use the formula for work $W = Fs$ $F = 5.0$ N and $s = 3.0$ m
b $W = \Delta KE$ $\Delta KE = 15$ J $KE_i = \frac{1}{2}mu^2 = \frac{1}{2} \times 0.40 \times 5.0^2 = 5.0$ J	Recall that work done is equal to the change in kinetic energy. The initial kinetic energy can be calculated using $m = 0.40$ kg and $u = 5.0$ m s^{-1}.
$\Delta KE = KE_f - KE_i$ $KE_f = \Delta KE + KE_i = 15 + 5.0 = 20$ J	Calculate the final kinetic energy as the change in kinetic energy plus the initial kinetic energy.

Force-displacement graphs

The formula $W = Fs$ can only be used when the magnitude of the applied force is constant. When the force applied changes with the displacement, we can produce a force-displacement graph (see Figure 2).

The area under the graph between two distances is equal to the work done (in J) over that interval. This can be calculated using geometric formulas like that for the area of a triangle (as is the case in Figure 2), or alternatively by counting the squares for curved graphs.

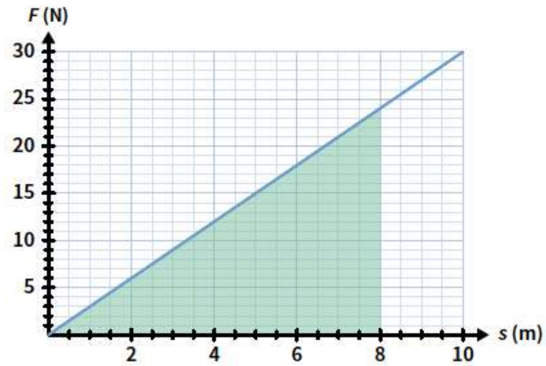


Figure 2 The shaded area represents the work done on the object from its starting position to a displacement of 8 metres.

USEFUL TIP

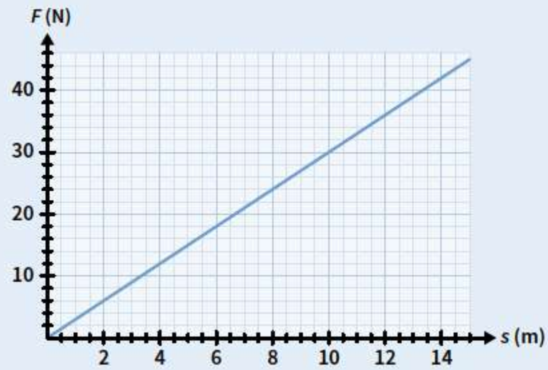
The VCE Study Design references a force-distance graph instead of a force-displacement graph. For the types of problems we will deal with, these two graphs are identical since there is no change in the direction of motion. However, in more complex situations, force-distance graphs are no longer accurate for calculating work done.

Worked example 3

Kaitlyn is pushing a 20 kg crate across a smooth floor from one side of the room to the other. This produces the following force-displacement graph:

a How much work is done on the crate between $s = 0$ m and $s = 10$ m?

b If the box starts from rest, calculate the magnitude of its final velocity at $s = 10$ m.



Working

a $W = \text{area under graph}$

$W = \frac{1}{2} \times 10 \times 30 = 150 = 1.5 \times 10^2$ J

Process of thinking

Work done is equal to the area under the force-displacement graph between $s = 0$ m and $s = 10$ m

b $\Delta KE = W$

$\therefore \Delta KE = KE_f - KE_i = 1.5 \times 10^2$ J

$KE_i = 0$ J

$\therefore KE_f = \frac{1}{2}mv^2 = 1.5 \times 10^2$ J

$\frac{1}{2} \times 20 \times v^2 = 1.5 \times 10^2$ J

$v = 3.9$ m s^{-1}

Recall that work done is equal to the change in kinetic energy.

The initial kinetic energy is zero since the crate is stationary at $s = 0$ m.

Solve for v with $m = 20$ kg.

Power 2.1.15.1

OVERVIEW

Power is equal to the change in energy (work done) per unit time. It measures the rate at which energy is being transferred or transformed.

THEORY DETAILS

We define power to be a measure of the rate at which the energy of a system or object is changed. Power is related to energy and time through the following formula:

$$P = \frac{E}{t}$$

P = power (W), E = energy transferred/transformed (J), t = time (s)

- The SI unit for power is watts (W), where 1 W is equal to 1 J s^{-1}.
- Power is a scalar quantity.
- Power is a measure of the rate of change of energy, not just the amount of energy that has been transferred/transformed.
- Power can also be expressed as $P = \frac{W}{t}$, where W = work done, however this is only applicable when the change in energy is caused by an applied force.

Worked example 4

A tow car does 75 kJ of work on a broken vehicle over the course of 24 seconds. Calculate the power output of this energy transfer.

Working

$E = W = 75 \times 10^3$ J

$P = \frac{E}{t} = \frac{75 \times 10^3}{24} = 3.1 \times 10^3$ W

Process of thinking

Convert the change in energy, $E = 75$ kJ, into SI units.
Calculate power using $t = 24$ s

Energy efficiency 2.1.16.1

OVERVIEW

An efficient transfer of energy is where minimal energy is lost to the environment due to resistive forces. We can calculate the efficiency of a system by dividing the final amount of useful energy by the total amount of energy supplied.

THEORY DETAILS

'Useful' energy is considered to be forms of energy like kinetic energy or potential energy that can be used to do additional work. When energy is converted into non-useful energy, it is irrecoverable.

The efficiency of an energy transfer is the amount of useful energy after the transfer divided by the total energy initially supplied. It is usually a measure of how much energy was lost due to resistive forces like friction and air resistance.

$$\eta = \frac{useful\ energy\ out}{total\ energy\ in}$$

η = efficiency (no units), useful energy out (J), total energy in (J)

- The efficiency is generally expressed as a decimal between 0 (perfectly inefficient) and 1 (perfectly efficient).
- You can assume that a system is perfectly efficient unless otherwise specified. In reality, however, this is impossible to achieve.

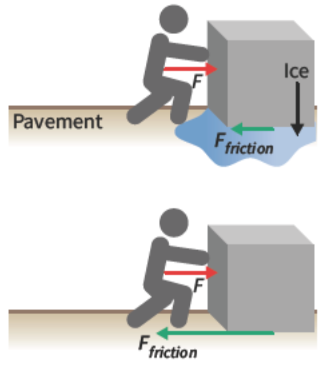


Figure 3 It is more efficient to push a box over ice than over pavement, since there will be less supplied energy lost due to friction.

Worked example 5

Shanesia is investigating the efficiency of pushing a box across her wooden floor. She does 150 J of work on a 2.5 kg box and then measures its velocity as 5.0 m s^{-1} at the point of release.

a **What was the efficiency of the energy transfer?**

b **Calculate how much energy was dissipated due to resistive forces.**

Working	**Process of thinking**
a $KE_f = \frac{1}{2}mv^2 = \frac{1}{2} \times 2.5 \times 5.0^2 = 31.25$ J	Calculate the final kinetic energy with $m = 2.5$ kg and $v = 5.0$ m s^{-1}.
$\eta = \frac{useful\ energy\ out}{total\ energy\ in}$ $\therefore \eta = \frac{31.25}{150} = 0.21$	Calculate the efficiency using the final kinetic energy and the *total energy in* = 150 J.
b $E_{resistive} = E_{supplied} - KE_f$ $\therefore E_{resistive} = 150 - 31.25 = 118.75 = 1.2 \times 10^2$ J	The difference in the total energy supplied and the final kinetic energy is equal to the energy lost to resistive forces.

Theory summary

- Kinetic energy is the energy associated with motion:
  - $KE = \frac{1}{2}mv^2$
  - $\Delta KE = \frac{1}{2}m(v^2 - u^2)$
- A force is said to have done work on an object if it displaces it in the direction in which the force is acting.
  - Work is equal to the product of force and displacement ($W = Fs$) or the area under a force-displacement graph.
  - When the applied force is in the same direction as motion, the work done is positive.
  - When the applied force is in the opposite direction of motion, the work done is negative.
- If no other change in energy but kinetic energy occurs, then $W = \Delta KE$.
- Power, P, is a measure of the change in energy per unit time.
  - $P = \frac{E}{t}$
- Energy efficiency is a measure of how much of the total energy supplied ends up as useful energy.
  - $\eta = \frac{useful\ energy\ out}{total\ energy\ in}$

KEEN TO INVESTIGATE?

YouTube video: Flipping Physics – Introduction to Power
youtu.be/BtHLmxvP7o0

CONCEPT DISCUSSION QUESTION

For many centuries, people have tried to invent a perpetual motion machine, a device that will never stop running and requires no further energy input other than to get it started (research the Capillary Bowl or Zimara's Windmill for examples). Discuss whether or not it is physically possible for such a device to exist.

Answers on page 509

Hints

What would the useful energy out compared to the useful energy in of this machine be?

What would this mean the efficiency of the machine would be? Is such a scenario physically possible in reality?

10B Questions

THEORY REVIEW QUESTIONS

Question 1

Consider an object with mass m kg, velocity v m s^{-1} and a kinetic energy of E J. For each scenario **a**-**e** described below, what would the corresponding kinetic energy be in terms of E?

a An object with velocity v and mass $2m$

b An object with velocity $2v$ and mass m

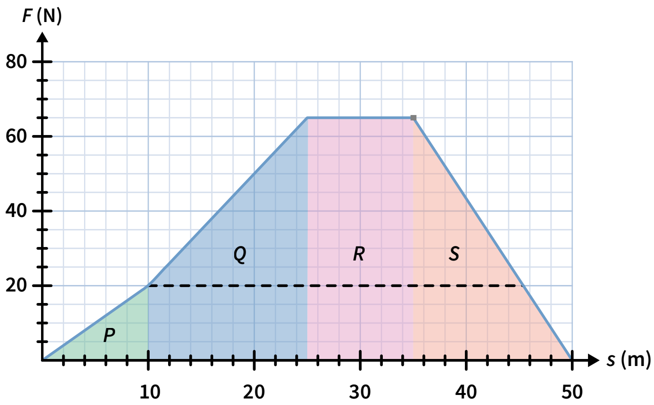
c An object with velocity $\frac{1}{4}v$ and mass m

d An object with velocity $\frac{1}{2}v$ and mass $2m$

e An object with velocity $-v$ and mass m

Question 2

For the force-displacement graph below, decide which combination of letters provides the work done over the specified range.



a From $s = 0$ m to $s = 10$ m.

b From $s = 0$ m to $s = 35$ m.

c From $s = 10$ m to $s = 50$ m.

Question 3

Match the types of work from the following list (I, II, III) to each of the scenarios.

Type of work

I The work being done on the object has a positive value,

II The work being done on the object has a negative value or

III No work is being done on the object.

Scenario

a Rachel picks up a pile of books from the floor.

b A ball rolls continuously along a smooth surface.

c A ball rolls 10 metres along a rough surface and comes to a stop

d Giselle tries to stop her car rolling down the hill by pushing against it.

e David tries to pick up a heavy object but cannot move it.

f Maria gets tired from carrying her backpack as she stands in line.

Question 4

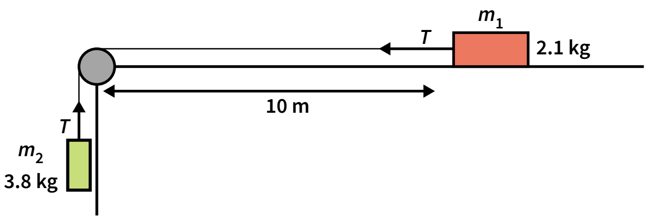
Fill in the gaps in the following paragraph.

__________ (Power/Energy efficiency) measures the rate at which the work is being done. If the work was done over a short period of time, this would mean that the power output was __________ (small/large/equal to the work done) compared to the same work being done over a longer period of time. In two different events, if the power supplied to two different objects is different, then this __________ (always means/does not always mean) that the magnitude of the work done on the two objects is also different.

DECONSTRUCTED EXAM-STYLE QUESTION

Question 5 (4 MARKS)

Stevie has set up the pulley system shown below:



The block, m_1, is being pulled across a rough surface by a massless string. The string is attached over a frictionless pulley to the other mass, m_2. When released, m_2 falls vertically and m_1 starts to accelerate from rest. There is a constant frictional force acting on m_1 of 15 N. Take the acceleration due to gravity, g, to be 9.8 m s^{-2}.

Prompts

a Once released m_2 accelerates at 3.77 m s^{-2}. Which of the following correctly describes the relationship between the tension in the string, T (in N), and the acceleration of m_2?

- **A** $T = m_2a_2 = 3.8 \times 3.77$
- **B** $T = m_2a_2 = (3.8 + 2.1) \times 3.77$
- **C** $3.8g - T = m_2a_2 = 3.8 \times 3.77$
- **D** $3.8g - T = m_2a_2 = (3.8 + 2.1) \times 3.77$

b Which of the following represents the net force (in N) acting on m_1? Take to the left as positive.

- **A** T
- **B** $15 - T$
- **C** $T - 2.1g$
- **D** $T - 15$

c What is the work done (in J) on m_1 after it has travelled for s m to the left?

- **A** $(T - 15) \times s$
- **B** $(T - 15) \times 10$
- **C** $T \times s$

Question

d Calculate how far m_1 would have to travel before it had 40 J of kinetic energy. (4 MARKS)

Adapted from 2010 VCAA Exam 1 Section A Q3-4

EXAM-STYLE QUESTIONS

This lesson

Question 6 (3 MARKS)

Sandra is moving some boxes around her office.

a Calculate how much work she does when she pushes a box from rest across the floor for 4.5 m with a force of 40 N. (1 MARK)

b What is the kinetic energy of the box after Sandra has pushed it 4.5 m? Ignore the effects of resistance forces. (2 MARKS)

Question 7 (2 MARKS)

When someone is holding an object off the ground, explain why in physics we would say that no work is being done, even though the person is applying a force to the object.

Question 8 (1 MARK)

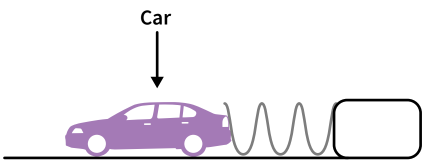
Billy has had a sugar rush and is trying to burn off some energy. He does so by running up and down his hallway, which is 15 metres long. If he completes 6 lengths in 22 seconds and uses 18 kJ of energy in the process, what is his power output?

Question 9 (2 MARKS)

Calculate how much work is done when a 2.5 kg stack of books is lifted off the floor at a constant speed to a height 1.5 metres above the ground. Take the acceleration due to gravity g to be 9.8 m s^{-2}.

Question 10 (5 MARKS)

A Year 11 Physics student is conducting an experiment where they use a horizontal spring to accelerate a model car from rest. Assume that there is no friction between the car and the surface it is travelling over, and unless otherwise stated, assume that the work done by the spring is 100% efficient.



a If the model car has a mass of 0.65 kg and the spring does 32.5 J of work on the model car, what is the velocity of the car as it loses contact with the spring? (2 MARKS)

b The student now uses a different model car of unknown mass. The spring does the same amount of work, and the velocity of the car as it loses contact with the spring is 6.7 m s^{-1}. Calculate the mass of the car. (2 MARKS)

c What would the unknown mass of the model car be if the work done by the spring was only 60% efficient and the car still had the same final velocity? (1 MARK)

Question 11 (4 MARKS)

A keen sledder is enjoying a weekend at the snow. At one point on a flat stretch of snow, they pull their sled behind them such that there is a constant force of 25 N in the rope and it makes an angle of 30 degrees with the horizontal. Assume that there is no friction between the sled and the snow.

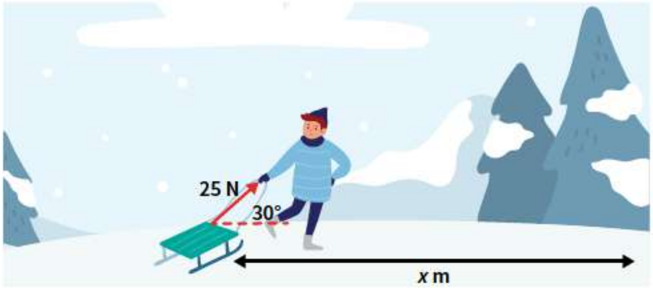


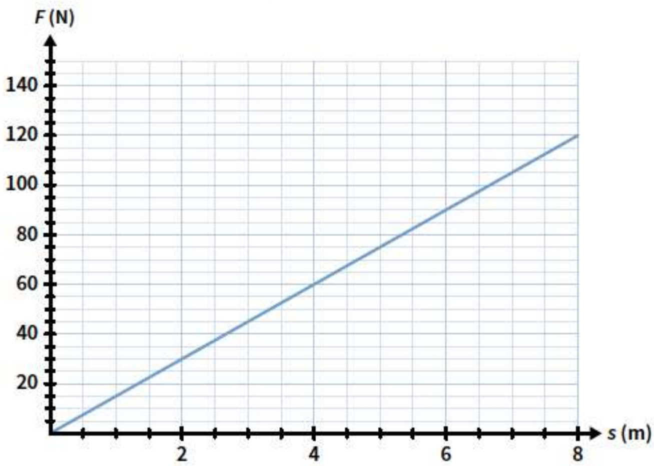
Image: Tartila/Shutterstock.com

a Explain why, as the sled is being pulled along, the magnitude of the force doing work on the sled is 25cos(30°) N and not 25 N. (2 MARKS)

b Calculate how far the sled would have to be pulled before it had 150 J of kinetic energy, assuming that it started from rest. (2 MARKS)

Question 12 (5 MARKS)

Jock is showing off his strength by pushing a 80 kg sofa along the floor. Corresponding graph is shown below:



a How much work does Jock do over the first 8 m? (1 MARK)

b If the velocity of the sofa was 0.75 m s^{-1} after Jock had pushed it for 8 m, calculate the force due to friction between the sofa and the floor. Assume that the force due to friction remained constant and that the sofa started from rest. (3 MARKS)

c Calculate the energy efficiency of the work done by Jock. (1 MARK)

Question 13 (6 MARKS)

A car is travelling along a road at 50 km h^{-1}. It makes a 90-degree turn left and keeps travelling at 50 km h^{-1}.

a What is the change in kinetic energy of the car before and after it has made the turn. (1 MARK)

b The car now approaches a red light with 80.0 kJ of kinetic energy and begins to decelerate at a constant rate. If the brakes produce a constant braking force of 1700 N on the road, calculate how far the car travels before coming to a stop. Assume that no other resistive forces act to slow the car down. (2 MARKS)

c If the car was travelling 10% faster, how much further would the car have travelled before it stopped? (3 MARKS)

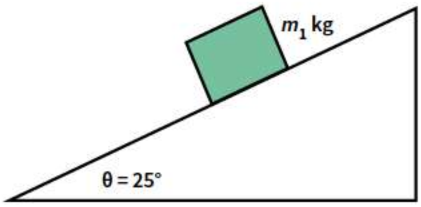
Previous lessons

Question 14 (2 MARKS)

Shawn is trying to calculate the cost of running his new Christmas LED light display. The display consists of 50 lights, each of which runs at 8.5 W. If the average price of household electricity was 31 cents/kWh, how much would it cost him if he ran it for 3 days straight?

Question 15 (3 MARKS)

Consider the system shown below.



There is a frictional force $F_f = 18$ N between m_1 and the inclined plane. Calculate the largest mass the block could have before it begins to slide down the plane.

Key science skills

Question 16 (2 MARKS)

Shian is conducting an experiment with the aim of measuring the relationship between the final velocity of a model car and the work done on it. She also wants to see how the mass of the car affects this final velocity. Every time she increases the work done, she also adds small weight plates to the back of the car. Comment on the validity of Shian's experimental procedure.

10C GRAVITATIONAL POTENTIAL ENERGY

Gravitational potential energy and the law of conservation of energy are useful tools to help us understand the transformations in energy of any object that changes height, from rocket ships to roller coasters.

10A Momentum and impulse	10B Work and kinetic energy	10C Gravitational potential energy	10D Springs

Study design dot point

- analyse and model mechanical energy transfers and transformations using energy conservation:
  - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
  - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
  - kinetic energy: $E_k = \frac{1}{2}mv^2$

Key knowledge units

Gravitational potential energy	2.1.14.1
Conservation of energy	2.1.14.4

Formulas for this lesson

Previous lessons		New formulas
10B	$KE = \frac{1}{2}mv^2$	$\Delta GPE = mg\Delta h$ change in gravitational potential energy
		$v = \sqrt{-2g\Delta h + u^2}$ final speed of an object moving in a gravitational field

Definitions for this lesson

gravitational potential energy the stored energy associated with the position of an object in a gravitational field

Gravitational potential energy 2.1.14.1

OVERVIEW

Gravitational potential energy is the energy stored by an object as a result of its position in a gravitational field. It can be calculated with $\Delta GPE = mg\Delta h$ or as the area underneath a gravitational force-height graph.

THEORY DETAILS

Gravitational potential energy is the name we give to the stored energy of an object due to its position in a gravitational field. All gravitational fields have a potential energy associated with them, however we will only be considering the gravitational field close to Earth's surface which is modelled as a uniform field with a strength of 9.8 N kg^{-1} (m s^{-2}).

The change in gravitational potential energy of an object is equal to the amount of energy required to move the object through a gravitational field, meaning the energy required to lift or drop an object.

It follows that lifting a heavier object, such as a dumbbell compared to a feather, will require a greater input of energy and hence the heavier object will experience a greater change in gravitational potential energy. Likewise, lifting two identical objects over a different distance will result in the object that is displaced more having a greater increase in gravitational potential energy.

$\Delta GPE = mg\Delta h$

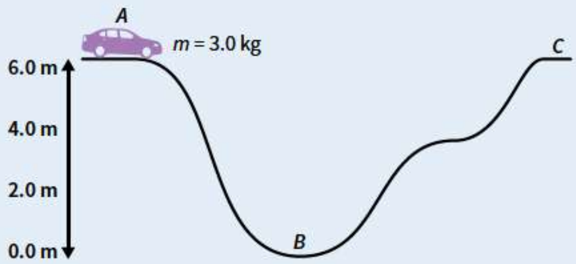
ΔGPE = change in gravitational potential energy (J), m = mass (kg), g = acceleration due to gravity (m s^{-2}), Δh = change in height (m)

Note that the VCE Physics Study Design uses the abbreviation E_g for gravitational potential energy. For the purposes of making an obvious distinction between different forms of energy, this book will usually use *GPE*.

Worked example 1

A 3.0 kilogram toy car is released from the top of a track with an initial height of 6.0 m as shown in the diagram. Take the acceleration due to gravity to be 9.8 m s^{-2}.

What is the magnitude of the change in gravitational potential energy of the toy car from point *A* to the points *B* and *C*?



Working	Process of thinking
Point *A* to Point *B*:	
$\Delta h = h_f - h_i = 0.0 - 6.0 = -6.0$ m	$h_i = 6.0$ m, $h_f = 0.0$ m, $m = 3.0$ kg, $g = 9.8$ m s^{-2}
$\Delta GPE = mg\Delta h = 3.0 \times 9.8 \times (-6.0)$	
$\Delta GPE = -176$ J	
$\Delta GPE = 1.8 \times 10^2$ J	As the question asks for the magnitude, we take a positive value to two significant figures.
Point *A* to Point *C*:	
$\Delta h = h_f - h_i = 6.0 - 6.0 = 0$ m	$h_i = 6.0$ m, $h_f = 6.0$ m, $m = 3.0$ kg, $g = 9.8$ m s^{-2}
$\Delta GPE = mg\Delta h = 3.0 \times 9.8 \times 0$	
$\Delta GPE = 0$ J	As point *C* and *A* have the same height we would expect the gravitational potential energy to be the same, so a change of 0 will be calculated.

Gravitational force-height graphs

We also know from Lesson 10B that the work done is equal to the change in energy of an object due to a force. Gravitational potential energy represents the object's potential to do work due to its height in a gravitational field. This means that the area under a gravitational force-height graph for an object close to Earth's surface represents its change in gravitational potential energy (Figure 1).

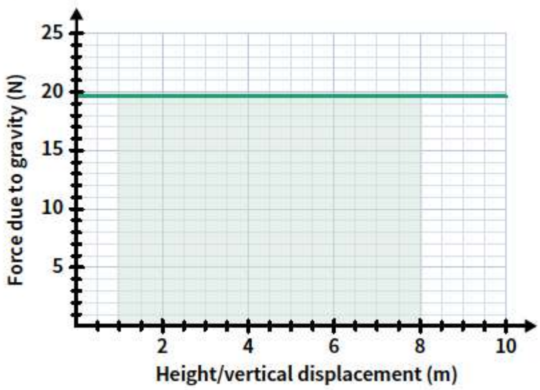


Figure 1 A gravitational force-height/vertical displacement graph for a 2 kg object. The force due to gravity remains constant so the graph shows a horizontal line. The shaded area represents the change in gravitational potential energy.

Conservation of energy 2.1.14.4

OVERVIEW

Energy is always conserved. This means that energy can be transformed from one type to another but never be created or destroyed. Hence, the total energy in a system will remain constant.

THEORY DETAILS

To find the total energy of a system we must add together all the different types of energy in the system. If kinetic energy and gravitational potential energy are the only relevant types of energy in a system, the total energy would be given by the following equation: $E_{total} = KE + GPE$.

Since energy is conserved (the total energy must be constant) we can equate the initial and final state giving us:

$$KE_i + GPE_i = KE_f + GPE_f$$

When finding GPE_i or GPE_f, we use the formula $GPE = mgh$ where the height, h, is taken from any point **as long as it is consistent**. For example, the height of a ball resting on a table could be measured from the floor or from the top of the table (or from any other reference height): it does not matter as long as we are consistent about the reference height throughout the problem we are solving.

We can expand the energy conservation equation by substituting in the formulas for gravitational potential energy and kinetic energy giving us: $\frac{1}{2}mu^2 + mgh_i = \frac{1}{2}mv^2 + mgh_f$.

By rearranging this equation (using $\Delta h = h_f - h_i$) we can find a formula for the final speed of an object moving in a gravitational field, as long as kinetic energy and gravitational potential energy are the **only** relevant types of energy:

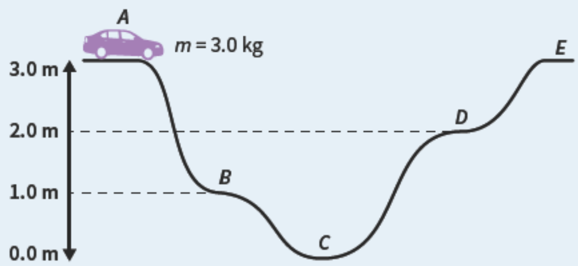
$$v = \sqrt{-2g\Delta h + u^2}$$

v = final speed ($m\ s^{-1}$), g = acceleration due to gravity ($m\ s^{-2}$), Δh = change in height (m), u = initial speed ($m\ s^{-1}$)

In real world systems, energy is often transformed into other forms such as thermal energy, sound energy, and the deformation of a material. This is called energy dissipation and it does not violate the conservation of energy principle. We will not consider these forms of energy in conservation of energy questions in VCE Physics Units 1&2.

Worked example 2

A 3.0 kilogram toy car is released from the top of a track with an initial height of 3.0 m. Its path is represented in the included diagram. Its speed is initially zero. Take the gravitational potential energy at point *C* to be zero.



Calculate

- **a** the gravitational potential energy of the car at point *A* above point *C*.
- **b** the kinetic energy of the car at point *B*.
- **c** the speed of the car at point *C*.
- **d** the total energy of the car at point *D*.

Working	Process of thinking
a $GPE = mg\Delta h = 3.0 \times 9.8 \times (3.0 - 0.0)$	$h_i = 0.0$ m, $h_f = 3.0$ m,
$GPE = 88.2 = 88$ J	$m = 3.0$ kg, $g = 9.8\ m\ s^{-2}$

b $KE_A + GPE_A = KE_B + GPE_B$ where $KE_A = 0$

$GPE_A = KE_B + GPE_B$

$mgh_A = KE_B + mgh_B$

$88.2 = KE_B + 3.0 \times 9.8 \times (1.0 - 0.0)$

$KE_B = 59$ J

At point *B*, a portion of the stored potential energy has been converted to kinetic energy. We equate the *KE* and *GPE* at points *A* and *B* and calculate the potential energy at point *B* with respect to point *C*.

$h_A = 0.0$ m, $h_B = 1.0$ m, $m = 3.0$ kg, $g = 9.8$m s^{-2}

c $v = \sqrt{-2g\Delta h + u^2}$

$v = \sqrt{-2 \times 9.8 \times (0.0 - 3.0) + 0.0^2}$

$v = 7.7$ m s^{-1}

Use the equation for the velocity of an object that is converting gravitational potential energy to kinetic energy.

$h_i = 3.0$ m, $h_f = 0.0$ m, $u = 0.0$ m s^{-1}, $g = 9.8$ m s^{-2},

d At point *A*:

$E_{total} = KE + GPE$, where $KE = 0$

$E_{total} = 0 + 88 = 88$ J

As energy is conserved, the total energy is the same at all points. So we will use point *A* to find the total energy as we have this information from part **a**.

Theory summary

- A change in gravitational potential energy can be calculated from
  - the equation $\Delta GPE = mg\Delta h$.
  - the area under a gravitational force-height graph.
- Energy can neither be created nor destroyed but can be transformed from one type of energy to another.
  - The initial energy equals the final energy of the system. For a system involving only kinetic energy and gravitational potential energy this gives us: $KE_i + GPE_i = KE_f + GPE_f$
  - $v = \sqrt{-2g\Delta h + u^2}$

KEEN TO INVESTIGATE?

oPhysics 'Ballistic pendulum' simulation
ophysics.com/e3.html

YouTube video: Veritasium – Bullet Block Experiment
youtu.be/vWVZ6APXM4w

CONCEPT DISCUSSION QUESTION

The Moon's orbit is within the Earth's gravitational field. It maintains a relatively constant distance from Earth's centre (Δh), has a constant mass, and a relatively constant speed.

Discuss how the Moon's velocity would change if it were to be moved further away from or closer to the Earth.

Answers on page 509

Hints

As the Moon gets closer to or further away from the Earth, what forms of energy are interchanged between?

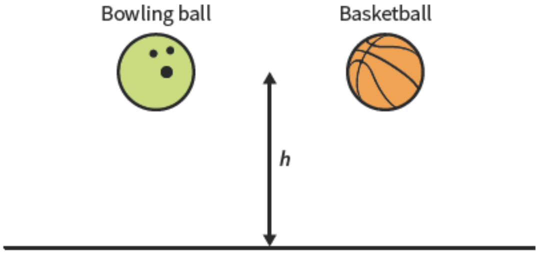
How would this change the Moon's speed?

10C Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–3.

A bowling ball and a basketball are dropped from the same height, *h*, at the same time. A bowling ball is much heavier than a basketball.



Question 1

At the height *h*, the bowling ball has

A the same gravitational potential energy as the basketball.

B more gravitational potential energy than the basketball.

C less gravitational potential energy than the basketball.

Question 2

When we ignore air resistance, the bowling ball will hit the ground

A with the same velocity as the basketball.

B with a greater velocity than the basketball.

C with a lower velocity than the basketball.

Question 3

When the balls hit the ground, the bowling ball will have

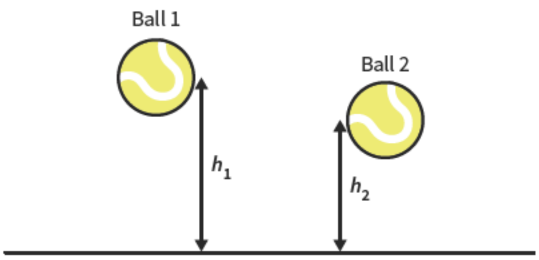
A the same kinetic energy as the basketball.

B less kinetic energy than the basketball.

C more kinetic energy than the basketball.

Question 4

Ball 1 and Ball 2 have identical mass but are dropped from different heights.



Which ball has a greater gravitational potential energy?

A Neither, they have the same gravitational potential energy.

B Ball 1

C Ball 2

Question 5

Fill in the gaps in the following paragraph assuming that the height is measured from the bottom of the slope.

A car rolls down a frictionless slope from rest. At the top of the slope the car has zero __________ (kinetic energy, gravitational potential energy). At the middle of the slope the car has some kinetic energy and some gravitational potential energy. At the bottom of the slope, as energy is __________ (conserved, not conserved), the car has zero __________ (kinetic energy, gravitational potential energy) and its __________ (kinetic energy, gravitational potential energy) is equal to the total energy of the system.

Question 6

A car is travelling at a constant speed of 10 m s^{-1} along a road at the top of a 30 m hill. Which equation is most appropriate to calculate the final kinetic energy of the car at the bottom of the hill?

A $KE_i = KE_f$

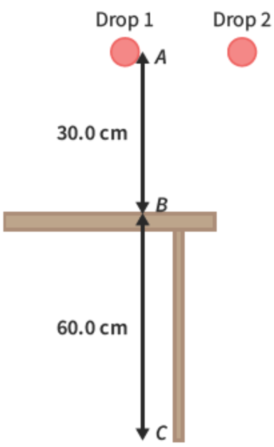
B $GPE_i = KE_f + GPE_f$

C $KE_i + GPE_i = KE_f$

D $KE_i + GPE_i = GPE_f$

Use the following information to answer Questions 7 and 8.

Whilst studying gravitational potential energy, students perform two drops with identical balls. The first drop (drop 1) is from a height of 30 cm above the table, and the second drop (drop 2) is from the same height but to the ground.



Question 7

Which position (*A-C*) is the most appropriate reference point for a student measuring the change in gravitational potential energy for the ball as it falls onto the table from a height of 30.0 cm?

Question 8

Which position (*A-C*) is the most appropriate reference point for a student measuring the change in gravitational potential energy for the ball as it falls to the ground?

DECONSTRUCTED EXAM-STYLE QUESTION

Question 9 (4 MARKS)

A 1.2 tonne cart is rolling along a roller coaster track towards a loop-the-loop. The loop-the-loop has a diameter of 40 m and the cart has a kinetic energy of 2.4×10^5 J at the top of the loop. Take the acceleration of gravity, g, to be $9.8\ \text{m s}^{-2}$ and assume that the cart has no motors or brakes with which it could accelerate or decelerate.

Prompts

a Which is the most appropriate equation to calculate the final velocity for a body moving through a gravitational field?

- **A** $v = \sqrt{-2g\Delta h + u^2}$
- **B** $KE = \frac{1}{2}mv^2$
- **C** $\Delta GPE = mg\Delta h$
- **D** $KE_i + GPE_i = KE_f + GPE_f$

b As it travels to the top of the loop-the-loop, the cart can be said to have

- **A** lost energy.
- **B** converted gravitational potential energy into kinetic energy.
- **C** converted kinetic energy into gravitational potential energy.
- **D** gained energy.

c Compared to when the cart is at the bottom of the loop-the-loop, at the top of the loop-the-loop the cart will have

- **A** the same speed.
- **B** a lower speed.
- **C** a greater speed.

Question

d Calculate the magnitude of the initial velocity of the cart before it enters the loop-the-loop. (4 MARKS)

EXAM-STYLE QUESTIONS

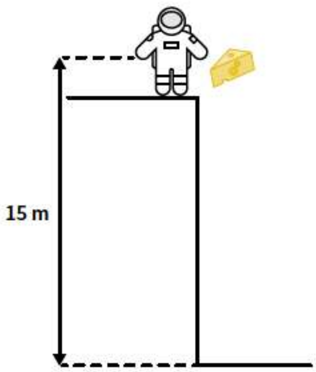
This lesson

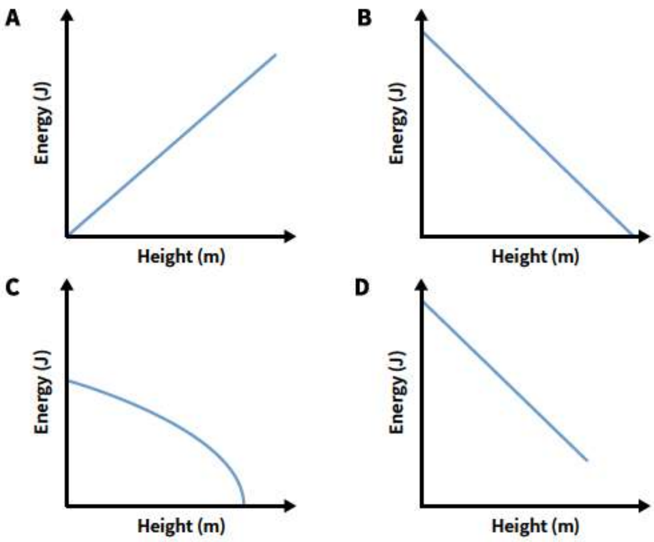
Question 10 (2 MARKS)

A skier is at a height of 750 m and wants to ride the chair lift to a height of 1000 m. If the difference in gravitational potential energy of the skier between these two altitudes is 1.76×10^5 J, calculate the skier's mass.

Question 11 (8 MARKS)

An astronaut on the moon drops a 1.0 kg moon rock from rest from a height of 15 m off a cliff. Take the gravitational potential energy at the bottom of the cliff to be zero.
The moon has an acceleration due to gravity of $1.62\ \text{m s}^{-2}$.





a Which graph (A-D) best shows the gravitational potential energy of the rock as a function of its height above the ground? Explain your answer. (2 MARKS)

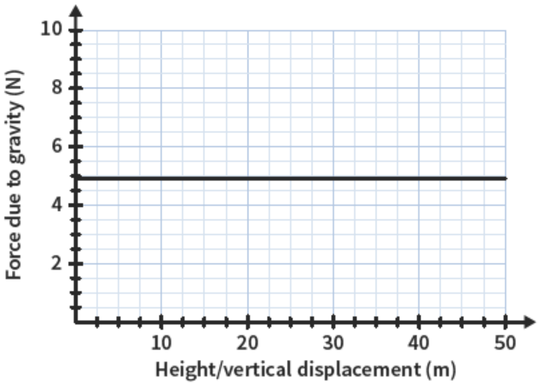
b Which graph (A-D) best shows the kinetic energy of the rock as a function of its height above the ground? Explain your answer. (2 MARKS)

c Calculate the kinetic energy of the rock right before it lands at the bottom of the cliff. (2 MARKS)

d Calculate the magnitude of the initial velocity of the rock when it has fallen 12 m. (2 MARKS)

Question 12 (5 MARKS)

A stone weighing 0.50 kg is launched from a height of 10 m and reaches a maximum height of 40 m. At its maximum height the stone is caught and stopped.



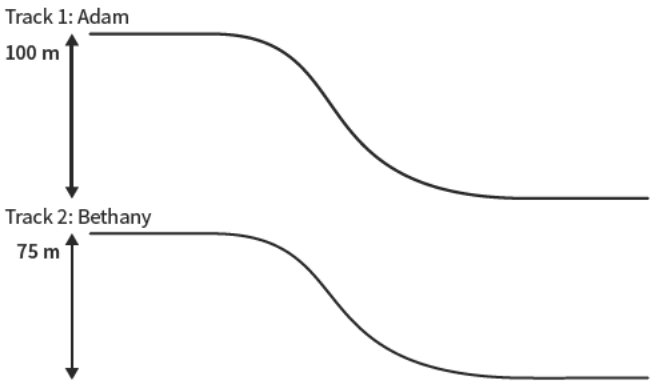
a Did the stone gain or lose gravitational potential energy as its height changed? (1 MARK)

b Use the graph to calculate the change in gravitational potential energy of the stone. (2 MARKS)

c Using your answer to part **b**, calculate the magnitude of the initial velocity of the stone. (2 MARKS)

Question 13 (5 MARKS)

Two cyclists, Adam and Bethany, are having a race. The race takes place on two tracks of the **same length**. Track 1 starts at a higher elevation of 100 m and track 2 starts at a lower elevation of 75 m. The tracks finish at the same point. Adam and Bethany agree that Adam will take track 1 and Bethany will take track 2. Adam weighs 75 kg and Bethany weighs 68 kg.

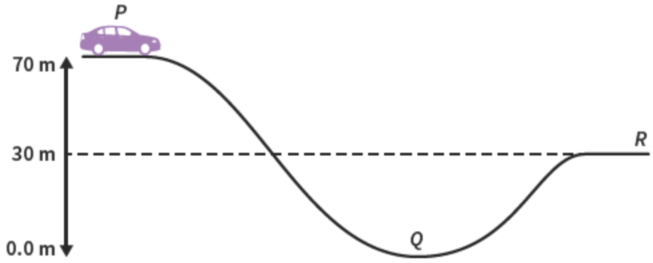


a Adam finishes the race with a velocity of 46.0 m s^{-1}. Calculate the magnitude of his velocity before descending the hill. (2 MARKS)

b What is the minimum kinetic energy that Bethany needs to achieve before descending the hill such that she can finish the race at the same speed as Adam? (3 MARKS)

Question 14 (4 MARKS)

A 950 kg car is moving at 12.0 m s^{-1} towards a dip in the road. Ignore any frictional forces.

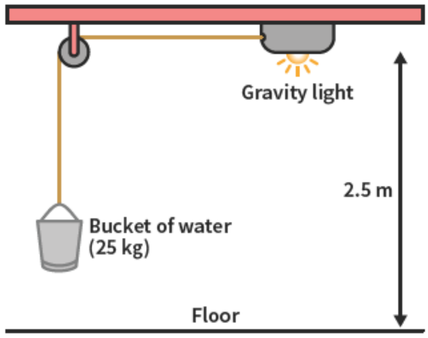


a Calculate the car's total energy at *Q*. (2 MARKS)

b Calculate the car's kinetic energy at *R*. (2 MARKS)

Question 15 (4 MARKS)

Students are testing a gravity light. A 25 kg bucket of water falls from a height of 2.5 m. The energy that it generates is converted into electrical energy to power a light requiring 2.0 J s^{-1}. Assume that the generator is ideal, meaning that it converts all the input energy to light energy.



a Ignoring any resistance forces and any energy conversions as a result of the bucket of water moving and colliding with the ground, calculate the maximum amount of energy that the bucket of water could generate. (2 MARKS)

b For how long will the light stay on as a result of the bucket of water falling from its maximum height to the ground? (2 MARKS)

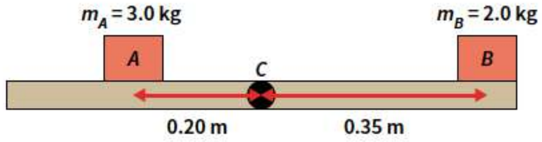
Previous lessons

Question 16 (3 MARKS)

Fuses are a safety feature in some devices. Describe how fuses work and provide a reason why they are less commonly used than other safety devices.

Question 17 (3 MARKS)

Blocks A and B are on a plank which can pivot around point C. Calculate the magnitude and direction of the net torque on the plank. Take acceleration due to gravity, g, to be 9.8 m s^{-2}.



Key science skills

Question 18 (2 MARKS)

Bella is trying to determine if the mass of a ball influences the time it takes for it to roll down a ramp. The first ball is 2.0 kg and Bella increases the mass of the ball by 1.0 kg each time. Bella discovers that she does not have a ball weighing 4.0 kg with the same radius as the others used, so uses a larger ball for this reading before continuing with balls of the original size.

Determine whether the experiment is valid and provide a reason why or why not.

10D SPRINGS

Have you ever considered how the suspension springs in a car act when you drive over a speed bump? This lesson will introduce the force and potential energy associated with ideal springs and apply them in the wider context of energy conservation and transformation.

10A Momentum and impulse	10B Work and kinetic energy	10C Gravitational potential energy	10D Springs

Study design dot points

- investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -k\Delta x$
- analyse and model mechanical energy transfers and transformations using energy conservation:
  - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
  - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
  - kinetic energy: $E_k = \frac{1}{2}mv^2$

Key knowledge units

Hooke's Law for springs	2.1.13.1
Strain potential energy	2.1.14.2

Formulas for this lesson

Previous lessons		New formulas
9A	$F_g = mg$	$F_s = -k\Delta x$ Hooke's Law
10B	$KE = \frac{1}{2}mv^2$	$SPE = \frac{1}{2}k(\Delta x)^2$ strain potential energy
10C	$GPE = mg\Delta h$	

Definitions for this lesson

compression the process of decreasing an object's length

extension the process of increasing an object's length

ideal spring a spring that obeys Hooke's law so that the force it exerts is proportional to its change in length

natural length the length of a spring when no external forces are acting on it

spring constant a value that describes the stiffness of a spring

strain potential energy the energy stored by the deformation of an object; also known as elastic potential energy or spring potential energy

Hooke's Law for springs 2.1.13.1

OVERVIEW

Hooke's law describes the linear relationship between the force and displacement of an ideal spring. The spring constant, k, represents the stiffness of a spring and determines the amount of force needed to compress or extend it.

THEORY DETAILS

In physics, a spring is any object that can store potential energy when it is deformed.
The natural length of a spring is its length when no external force is applied to it. When springs are deformed from their natural length through stretching or compression, they will produce a force which acts to restore their natural length.

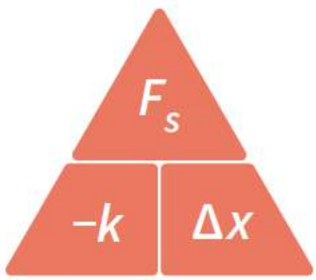


Figure 1 The formula triangle for Hooke's Law

An ideal spring is one where this force increases linearly with the displacement from its natural length. For example, if an ideal spring stretched by 10 cm produced a force of 5 N, then when stretched by 20 cm it would produce a force of 10 N. Unless otherwise stated, all springs in this lesson can be considered ideal.

Hooke's law is used to calculate the restoring force exerted by the spring to return to its natural length.

> $F_s = -k\Delta x$
>
> F_s = spring restoring force (N), k = spring constant (N m^{-1}), Δx = displacement from natural position (m)

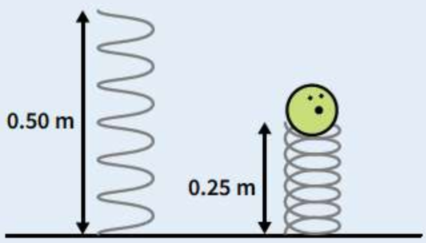
- The spring constant, k, is a property of a spring's material and is a measure of the force produced by the spring when it is displaced. The spring constant
  - is measured in N m^{-1},
  - is always positive,
  - and can be thought of as the stiffness of a spring.
- An ideal spring with a spring constant of 100 N m^{-1} will require 100 N of applied force to be compressed or stretched by 1 m.
- A spring will always produce a force in the **opposite direction to its displacement** in order to return to its natural length, and this is represented by the negative sign in Hooke's Law.
  - This negative sign is often excluded as it is common to deal with magnitudes of forces, therefore we would use $F_s = k\Delta x$ in our calculations.
- When a spring is in its natural position (neither compressed nor stretched, $\Delta x = 0$) it will not exert a force ($F_s = -k\Delta x = 0$).
- Many elastic objects besides springs may obey Hooke's law, such as elastic bands, but springs will be the most commonly used in VCE Physics.

When the restoring force of a spring acting on an object is opposed by another force such that the net force is zero, the spring will remain in its compressed or extended position. For an object attached to a vertical spring, when the force due to gravity acting on the object has the same magnitude as the restoring force of the spring ($mg = k\Delta x$), the net force on the object is zero. This is often called the **equilibrium position**.

- This is the position where an object attached to a spring will come to rest over a period of time when friction is present.

Worked example 1

An ideal spring has a spring constant of 200 N m^{-1} and a natural length of 0.50 m. When a bowling ball is at rest on the spring such that it is in the equilibrium position, the spring is compressed to a length of 0.25 m.



a What is the magnitude of the displacement, Δx, of the spring from its natural length?

b Determine the force produced by the spring.

c Calculate the mass of the bowling ball. Take the acceleration due to gravity, g, to be 9.8 m s^{-2}.

Working	Process of thinking
a $\Delta x = 0.50 - 0.25 = 0.25$ m	Δx is the difference between the spring's natural length, 0.50 m, and compressed length, 0.25 m
b $F_s = k\Delta x$	The magnitude of the force is given by Hooke's Law: $F_s = k\Delta x$
$F_s = 200 \times 0.25 = 50$ N	$k = 200$ N m^{-1}, $\Delta x = 0.25$ m
The spring produces a force of 50 N upwards.	The direction of the force is in the opposite direction to its downwards displacement, so upwards.

c $mg = k\Delta x$

As the bowling ball is in the equilibrium position, the magnitude of the spring force will be equal to the force due to gravity of the bowling ball: $mg = k\Delta x$

$m \times 9.8 = 200 \times 0.25$

$k = 200 \text{ N m}^{-1}$, $\Delta x = 0.25$ m, $g = 9.8 \text{ m s}^{-2}$

$m = 5.1$ kg

Strain potential energy 2.1.14.2

OVERVIEW

Strain potential energy represents the energy that is stored in a spring when it is compressed or extended. It can be transformed into gravitational potential energy or kinetic energy in line with the law of conservation of energy.

THEORY DETAILS

When a force is applied that stretches or compresses a spring, work is being done and energy is stored within the spring as strain potential energy. Strain potential energy represents the spring's potential to do work as it returns to its natural length. When the spring returns to its natural length this potential energy will be converted to other forms, usually kinetic energy and/or gravitational potential energy.

$$SPE = \frac{1}{2}k(\Delta x)^2$$

SPE = strain potential energy (J), k = spring constant (N m^{-1}), Δx = displacement from natural position (m)

Note that the VCE Physics Study Design uses the abbreviation E_s for strain potential energy. It is also known as elastic potential energy or spring potential energy. For the purposes of making an obvious distinction between different forms of energy, this book will usually use *SPE*.

As learned previously in Chapter 10, the total energy of a system is always conserved. This means we can equate the total energy of the initial state of a spring-mass system with the total energy of the final state of the system to determine unknown quantities.

$$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$$

PROBLEM SOLVING PROCESS

How to solve a problem using conservation of energy:

1. Write out the conservation of energy statement:

   $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

2. Find the terms that are equal to zero.
   - **a** When $v = 0$, then $KE = 0$
   - **b** When $h = 0$, then $GPE = 0$
   - **c** When $\Delta x = 0$, then $SPE = 0$

3. Rewrite the equation but ignore the terms that are equal to zero.

   For example: $SPE_i = KE_f + GPE_f$

4. Substitute the formulas for the unknown energies.

   For example: $\frac{1}{2}k(\Delta x)_i^2 = \frac{1}{2}mv^2 + mgh_f$

5. Substitute the known values into the equation and solve.

In practice, energy will be dissipated to the environment commonly in the form of thermal energy and in the permanent deformation of the spring material. This will not be considered in Unit 1 & 2 VCE Physics.

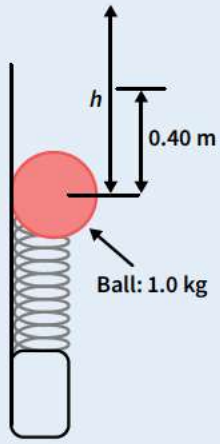
Worked example 2

An ideal spring is being used to launch a 1.0 kg ball vertically upwards. The spring is initially compressed by 0.40 m and has a spring constant of 80 N m^{-1}.

a Calculate the strain potential energy initially stored in the spring.

b Determine the maximum speed of the ball.

c Calculate the maximum height, h, that the ball reaches above its starting position.



Working	Process of thinking
a $SPE = \frac{1}{2}k(\Delta x)^2$	Use the strain potential energy equation: $SPE = \frac{1}{2}k(\Delta x)^2$
$SPE = \frac{1}{2} \times 80 \times 0.40^2 = 6.4$ J	$k = 80$ N m^{-1}, $\Delta x = 0.40$ m
b $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$	The ball is travelling fastest just after being released. Use energy conservation.
When the spring is initially compressed: • $KE_i = 0$ as the ball starts from rest. • $GPE_i = 0$ as the ball starts from the lowest point.	Initial state: ball at rest on the compressed spring.
Just after the ball is released from the spring: • $SPE_f = 0$ as the spring has returned to its natural length.	Final state: ball just above the spring with spring at natural length.
$SPE_i = KE_f + GPE_f$	Ignoring the values that are zero, we can rewrite the energy statement.
$\frac{1}{2}k(\Delta x)^2 = \frac{1}{2}mv^2 + mgh$	Substitute the formulas for the unknown energies.
$\frac{1}{2} \times 80 \times 0.40^2 = \frac{1}{2} \times 1.0 \times v^2 + 1.0 \times 9.8 \times 0.40$ $v = 2.2$ m s^{-1}	$k = 80$ N m^{-1}, $\Delta x = h = 0.40$ m, $m = 1.0$ kg
c $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$	Use energy conservation. Initial state: ball at rest on the compressed spring (same as in part **b**).
At the highest point: • $KE_f = 0$ as the ball is instantaneously at rest when it reaches its maximum height. • $SPE_f = 0$ as the spring has returned to its natural length.	Final state: ball at its highest point.
$SPE_i = GPE_f$	Ignoring the values that are zero, we can rewrite the energy statement.
$\frac{1}{2}k(\Delta x)^2 = mgh$	Substitute the formulas for the unknown energies.
$\frac{1}{2} \times 80 \times 0.40^2 = 1.0 \times 9.8 \times h$ $h = 0.65$ m	$k = 80$ N m^{-1}, $\Delta x = 0.40$ m, $m = 1.0$ kg, $g = 9.8$ m s^{-2}

Spring force-displacement graphs

A spring force-displacement graph is a useful way of displaying the properties of a spring, and shows the magnitude of the spring force for a range of displacements of the spring. For ideal springs, their spring force-displacement graph will be linear (a constant gradient) modelled by Hooke's Law.

Table 1 Key features of spring force-displacement graphs

Spring force-displacement graph feature	What the feature represents
Gradient	Spring constant (k)
Area under the graph	Change in strain potential energy (ΔSPE)
Vertical axis value	Spring force (F_s)

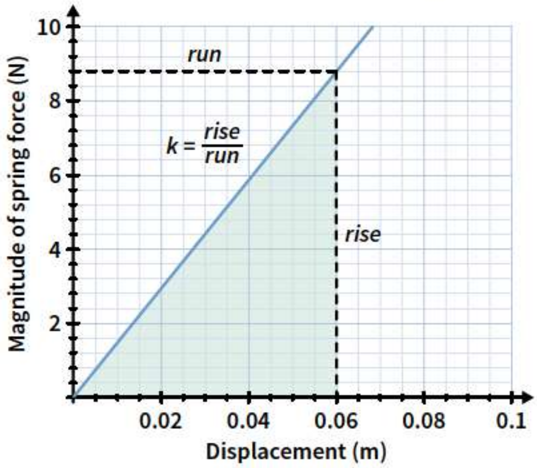


Figure 2 The gradient of this spring force-displacement graph is the spring constant, $k = \frac{8.8-0}{0.06-0} = 1.5 \times 10^2\ \text{N m}^{-1}$. The shaded area shows the change in strain potential energy, $\frac{1}{2} \times 0.06 \times 8.8 = 0.26\ \text{J}$, and the specific vertical axis value shows the magnitude of the spring force, 8.8 N, when the spring is displaced 0.06 m from its natural length.

Theory summary

- Hooke's law relates the spring force to the displacement of an ideal spring: $F_s = -k\Delta x$
- Strain potential energy can be calculated by $SPE = \frac{1}{2}k(\Delta x)^2$
- Conservation of energy:
  - Energy can be transformed between kinetic, gravitational and strain potential energy.
  - The total energy in a system must remain constant.
  - In a closed system: $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$
- On a spring force-displacement graph for an ideal spring:
  - the graph is linear, with the gradient equal to the spring constant, k,
  - the area under the graph is equal to the change in strain potential energy, SPE,
  - the vertical axis value is the spring force, F_s.

KEEN TO INVESTIGATE?

PhET 'Masses and springs' simulation
phet.colorado.edu/en/simulation/masses-and-springs

YouTube video: Flipping Physics – Hooke's Law Introduction – Force of a Spring
youtu.be/EbVeoJBjHTw

CONCEPT DISCUSSION QUESTION

Rubber bands can be thought of as similar to ideal springs since they can store strain potential energy and obey Hooke's Law for small displacements. They can be shot from someone's hand by stretching it and then releasing it, as shown in the included diagram. If the objective is for a rubber band to be shot at a maximum speed, discuss whether a small, stiff rubber band or a larger, stretchier rubber band would be preferred.

Answers on page 509

Image: Sharomka/Shutterstock.com

Hints
How do the properties of the two rubber bands compare?
How do these properties affect the strain potential energy stored in a stretched rubber band?
How will these factors relate to the maximum speed of the rubber band?

10D Questions

THEORY REVIEW QUESTIONS

Question 1

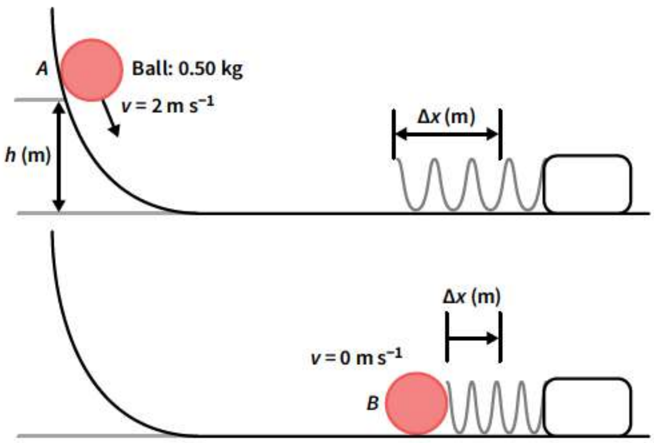
The spring force increases __________ (linearly with/with the square of) displacement and the strain potential energy increases __________ (linearly with/with the square of) displacement.

Question 2

On a spring force-displacement graph, the spring constant is equivalent to the __________ (gradient/area under the graph) and the strain potential energy is equivalent to the __________ (gradient/area under the graph).

Question 3

A ball is pushed down a ramp such that it has an initial speed of 2 m s^{-1} at position *A*, before compressing a spring and momentarily coming to rest at position *B*.

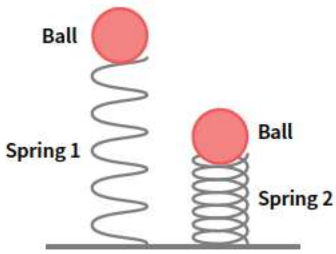


Which of the following lists the non-zero energies at position *A* and position *B*?

	Non-zero energies at position *A*	Non-zero energies at position *B*
A	*GPE*	*SPE* and *KE*
B	*GPE* and *KE*	*SPE*
C	*GPE*, *KE* and *SPE*	
D	*KE* and *SPE*	*GPE*

Use the following information to answer Questions 4–6.

Two balls of identical mass are at rest on two springs of the same length but that have different spring constants. Spring 2 is compressed more than Spring 1.



Question 4

Which of the following options identifies the spring with the greater spring constant, *k*?

A Spring 1

B Spring 2

C They have the same spring constant.

D Not enough information is given.

Question 5

Which of the following options identifies the spring producing the greatest upwards force, F_s?

A Spring 1

B Spring 2

C They are producing the same upwards force.

D Not enough information is given.

Question 6

Which of the following options identifies the spring that has the **greatest strain potential energy**, *SPE*?

A Spring 1

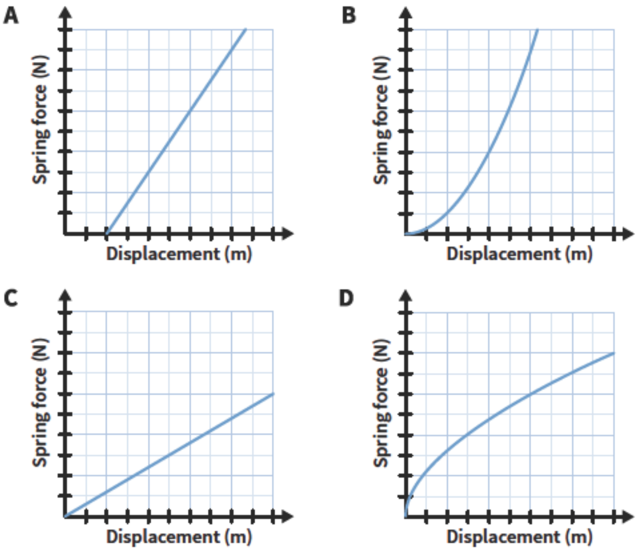
B Spring 2

C They both have the same strain potential energy.

D Not enough information is given.

Question 7

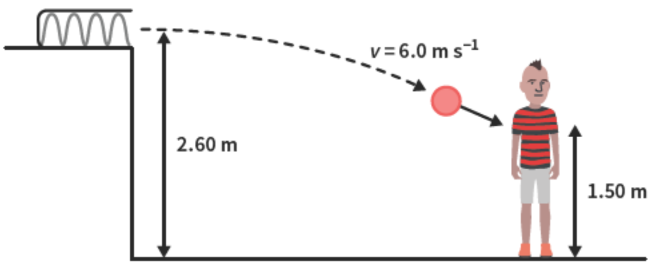
Which of the following spring force-displacement graphs correctly represents an ideal spring?



DECONSTRUCTED EXAM-STYLE QUESTION

Question 8 (5 MARKS)

In a school playground, a teenager named Ex Tension uses an ideal spring to launch a bean bag towards one of his friends, Hook Slaw. It is launched from a height of 2.60 m and strikes Hook Slaw at a height of 1.50 m and speed of 6.0 m s^{-1} before falling to the ground. The bean bag has a mass of 0.15 kg. Ex Tension knows that when the spring is compressed by 0.35 m, there is a restoring force of 60 N.



Prompts

a Which of the following values represents the spring constant, *k*, of the ideal spring?

A 11 N m^{-1}

B 87 N m^{-1}

C 171 N m^{-1}

D 400 N m^{-1}

b Which of the following correctly lists the non-zero energies when the bean bag is at rest and compressing the spring?

A *SPE*

B *SPE*, *GPE*

C *SPE*, *GPE*, *KE*

D None of the above

c Which of the following correctly lists the non-zero energies just before the bean bag strikes Hook Slaw?

A *KE*

B *KE*, *GPE*

C *KE*, *GPE*, *SPE*

D None of the above

d Which of the following shows the conservation of energy equation for this situation?

A $SPE_i = KE_f$

B $SPE_i = KE_f + GPE_f$

C $SPE_i + GPE_i = KE_f + GPE_f$

D $SPE_i + GPE_i + KE_i = KE_f + GPE_f$

Question

e Determine the compression of the spring used to launch the bean bag. (5 MARKS)

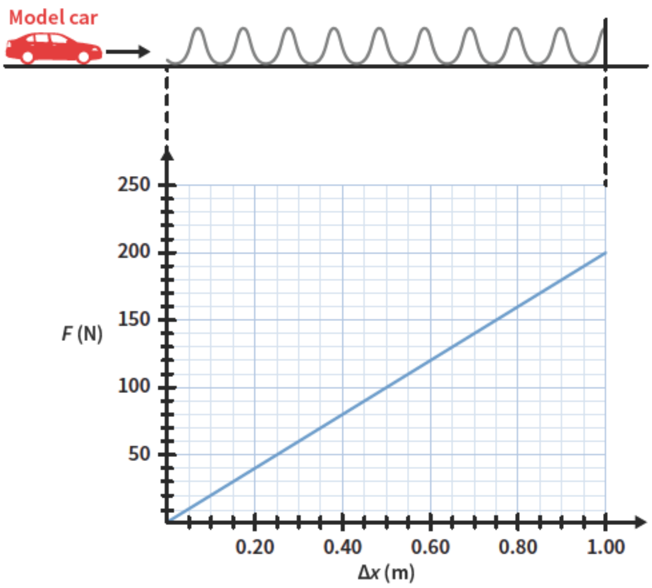
EXAM-STYLE QUESTIONS

This lesson

Question 9 (3 MARKS)

As shown in the included diagram, a model car is moving towards an ideal spring which it collides with and then compresses.

The model car compresses the ideal spring by 0.80 m from its natural position before coming to rest. The spring force-displacement graph is included. Ignore the effects of friction.



a From the included spring force-displacement graph, which of the following values best represents the spring constant, k? (1 MARK)

A 100 N m^{-1}

B 150 N m^{-1}

C 200 N m^{-1}

D 250 N m^{-1}

b Before colliding with the spring, what is the kinetic energy of the car? (1 MARK)

A 64 J

B 80 J

C 100 J

D 128 J

c What force does the spring exert on the car when compressed 0.40 m? (1 MARK)

A 60 N

B 80 N

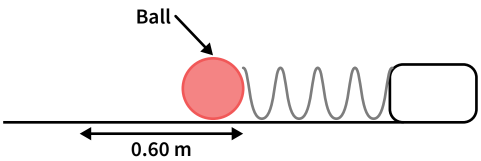
C 100 N

D 120 N

Adapted from 2017 VCAA Exam Section A Q12–13

Question 10 (6 MARKS)

A ball of mass 0.35 kg is held against an ideal spring with a spring constant of 200 N m^{-1}. The spring is compressed from its unstretched position by 0.60 m. The ball is then released and fired across a frictionless surface.



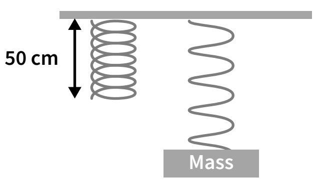
a At the moment the ball is released, determine the magnitude of the spring force which acts on it. (1 MARK)

b What is the strain potential energy stored in the compressed spring? (2 MARKS)

c Calculate the maximum speed of the ball after being released. (3 MARKS)

Question 11 (4 MARKS)

Students in a physics class are attempting to find the spring constant, k, of an ideal spring by hanging a number of 30 g masses from it and measuring the extension, Δx. Their data is shown in the included table.



Number of 30 g masses	Extension of spring, Δx
0	0
1	10 cm
2	20 cm
3	30 cm

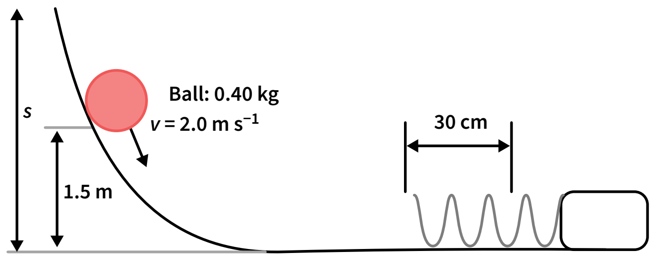
a Determine the value of the spring constant, k. (2 MARKS)

b When the spring has a **total length** of 80 cm, calculate the amount of strain potential energy in the spring. (2 MARKS)

Adapted from 2016 VCAA Exam Section B Detailed study 1 Q3

Question 12 (9 MARKS)

A ball of mass 0.40 kg is positioned on a ramp at a height of 1.5 m. It is then pushed down the ramp such that it has a speed of 2.0 m s^{-1}. At the bottom of the ramp it collides with an ideal spring and compresses it by 30 cm from its unstretched position.



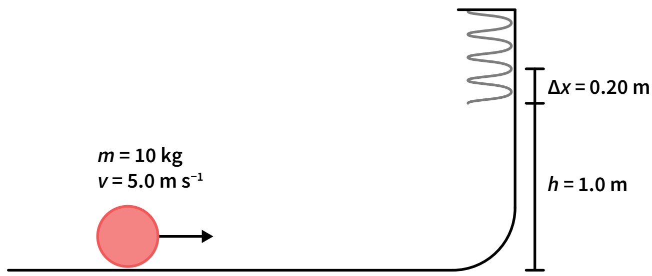
a Calculate the spring constant, k, of the spring. (3 MARKS)

b Determine the maximum speed of the ball. (3 MARKS)

c If the ball is then launched from the compressed spring back towards its initial position, calculate the maximum height, s, it will reach. (3 MARKS)

Question 13 (8 MARKS)

A ball of mass 10 kg has a speed of 5.0 m s^{-1} on a frictionless surface. The ball travels up a ramp where it compresses an ideal spring by 0.20 m before momentarily coming to rest. The spring is positioned such that it contacts the ball at a height of 1.0 m.



a Show that the spring constant, k, of the spring is $3.7 \times 10^2 \text{ N m}^{-1}$. (2 MARKS)

b What is the acceleration of the ball when the spring is compressed 0.20 m? (2 MARKS)

c Calculate the speed of the ball when the spring is compressed by 0.05 m. (3 MARKS)

d What is the velocity of the ball after travelling down the ramp and returning to its starting position? (1 MARK)

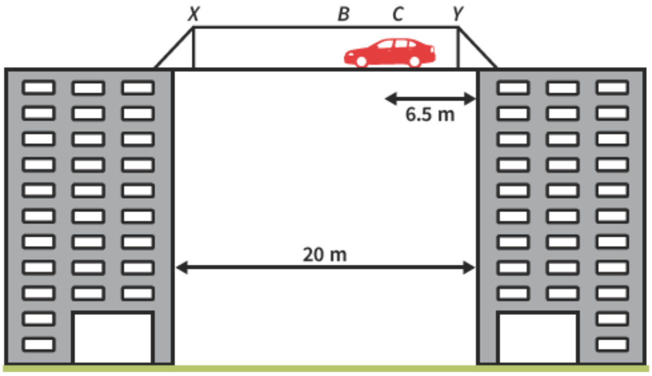
Previous lessons

Question 14 (3 MARKS)

Describe the function and operation of a circuit breaker and a residual current device (RCD).

Question 15 (4 MARKS)

Engineers have designed a bridge to transport cars between two multilevel car parks. The uniform bridge with a length of 20 m has a centre at B, a mass of 5.0×10^4 kg and is supported by the buildings on each end, at points X and Y. A car of mass 2.2×10^3 kg is 6.5 m from the right building, at position C.



a Calculate the magnitude of the force acting up on the bridge by the **left building**, F_X. (2 MARKS)

b Calculate the magnitude of the force acting up on the bridge by the **right building**, F_Y. (2 MARKS)

Key science skills

Question 16 (7 MARKS)

As part of a practical investigation, students are investigating a vertical spring system made of a single ideal spring and a platform. In the investigation, students place various masses on the platform and measure the compression of the spring. Their results are shown in the included table. The ruler used to measure the compression has an uncertainty of ± 3 mm. Take acceleration due to gravity, g, to be 10 m s^{-2}.

Mass (g)	Compression, Δx (mm)
0	0
150	16
300	33
450	43
600	61

a On a set of axes:

- Plot the students' data showing force (N) against compression (m).
- Include appropriate uncertainty bars for the compression of the spring.
- Include appropriate scales, units and axis labels.
- Include a line of best fit.

(5 MARKS)

b Determine the spring constant, k. (2 MARKS)

CHAPTER 10 REVIEW

These questions are typical of 40 minutes worth of questions on the VCE Physics Exam.

TOTAL MARKS: 30

SECTION A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1

Mercury Williams serves a 56 g tennis ball with an average contact force of 140 N. If the ball leaves the racket with a speed of 50 m s^{-1}, and assuming the ball is initially at rest, for how long was the ball in contact with the racket strings?

A 0.020 s

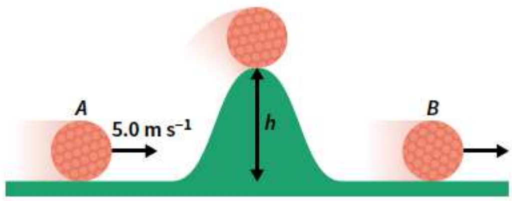
B 0.16 s

C 0.050 s

D 0.020 ms

Use the following information to answer Questions 2 and 3.

Consider the following scenario where a 300 g ball rolls up and over a narrow hill of height h m. The ball has a velocity of 5.0 m s^{-1} at point A and just makes it to the top of the hill, before continuing down the other side. Assume that there is negligible friction acting on the ball and take the acceleration due to gravity, g, to be 9.8 m s^{-2}.



Question 2

What is the value of h?

A 0.26 m

B 1.3 m

C 0.38 m

D 2.6 m

Question 3

What is the speed of the ball when it reaches point B?

A 0 m s^{-1}

B It depends on how far B is from the top of the hill.

C It depends on how long it takes for the ball to roll down the hill.

D 5.0 m s^{-1}

Question 4

A force is applied to extend an ideal spring by x m. This gives it 50 J of strain potential energy. How much strain potential energy would the spring have if the extension were increased to $4x$ m? Assume the new extension is within the elastic limit of the spring.

A 200 J

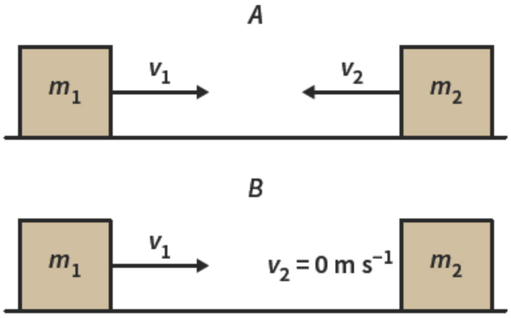
B 800 J

C 12.5 J

D It would depend on the spring constant, k.

Question 5

Consider the following two collisions: (*A*) two blocks moving in opposite directions collide and (*B*) a moving block collides with a stationary block. After both collisions, the blocks join together and move off as one body. In both cases, $m_1 > m_2$. In *A*, v_1 and v_2 are unknown and in *B*, $v_2 = 0\text{ m s}^{-1}$. Which of the following statements must be true?



A After the collision, the joined blocks in both *A* and *B* must move off to the right by the conservation of momentum, regardless of whether v_1 or v_2 is greater.

B In *B*, the magnitude of the impulse experienced by m_2 will be greater than the magnitude of the impulse experienced by m_1.

C In *B*, the magnitude of the velocity of m_1 after the collision will be less than the magnitude of its velocity before the collision.

D In *A*, the force applied on m_2 by m_1 is greater than the force applied on m_1 by m_2.

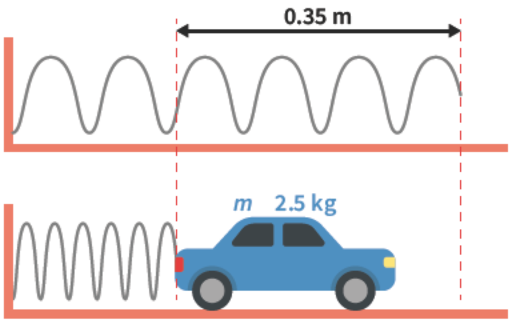
SECTION B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (5 MARKS)

Aubrey is using a model car and a spring to investigate work and momentum. The car of mass 2.5 kg is held against a spring, compressing it by 0.35 m from its natural length, and then released, as shown in the included diagram.



a A force of 70 N is required to hold the car in place. Show that the spring constant, *k*, is $2.0 \times 10^2\text{ N m}^{-1}$. (1 MARK)

b If the car is subject to a constant frictional resistance of 3.10 N when it has left contact with the spring, determine how far the car will travel past the natural length of the spring before coming to rest. Assume there is negligible friction acting on the car when the spring is extending. (3 MARKS)

c Aubrey completes a second test where she does not compress the spring as much, and the car moves off at a speed of 1.8 m s^{-1}. Calculate the magnitude of the impulse given to the car by the spring. Include an appropriate unit. (1 MARK)

Adapted from 2016 VCAA Exam Section A AoS 1 Q4

Question 7 (7 MARKS)

An AFL umpire bounces the ball after a goal by throwing it into the ground. The ball has a mass of 450 g and is thrown vertically downwards so that it impacts the ground at 12.0 m s^{-1} and rebounds off at 9.0 m s^{-1} vertically upwards.

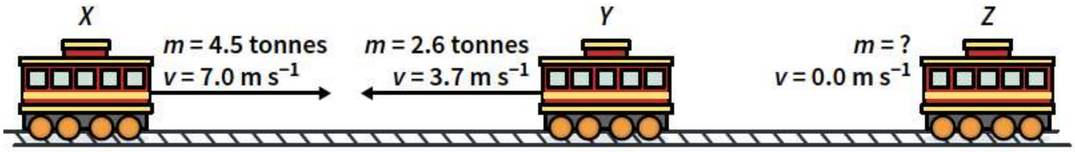
a What is the change in momentum of the ball? Is this a violation of the law of conservation of momentum? Why or why not? (2 MARKS)

b What is the maximum height the ball reaches after leaving the ground? (2 MARKS)

c Over small ranges of compression, the ball can be modelled as an ideal spring. If the ball is compressed by 5.8 cm on impact with the ground before rebounding up, calculate the spring constant, *k*. (3 MARKS)

Question 8 (7 MARKS)

There has been an accident on the railway crossing and two trolley carts X and Y are on a collision course as shown in the included diagram. Trolley cart X has a mass of 4.5 tonnes and is moving to the right at 7.0 m s^{-1}. Trolley cart Y has a mass of 2.6 tonnes and is moving to the left at 3.7 m s^{-1}. After the collision, the trolley carts join together and move off as one.



a What is the velocity v of the trolley carts immediately after the collision? (3 MARKS)

b If trolley cart X collides with trolley cart Y with an average force of 25 000 N, calculate the duration of the collision, t. (2 MARKS)

c The combined system is now set to collide with a third trolley cart Z. Explain why, regardless of the mass of Z is, it is impossible for it to remain stationary after the collision. (2 MARKS)

Question 9 (6 MARKS)

Friederick, a 75.0 kg man, is going bungee jumping for the first time. The bungee cord can be modelled as an ideal spring with a spring constant, k, of 300 N m^{-1}.

a After the jump, Friederick bounces up and down before eventually coming to rest. Find the extension of the bungee cord at this point. (1 MARK)

b During the jump, Friederick reaches the lowest point after he has fallen 65.0 m. Use this information to find the natural length of the bungee cord. (3 MARKS)

c What is Friederick's speed when he has fallen 25 m? (2 MARKS)

UNIT 2, AOS 1 REVIEW

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

SECTION A

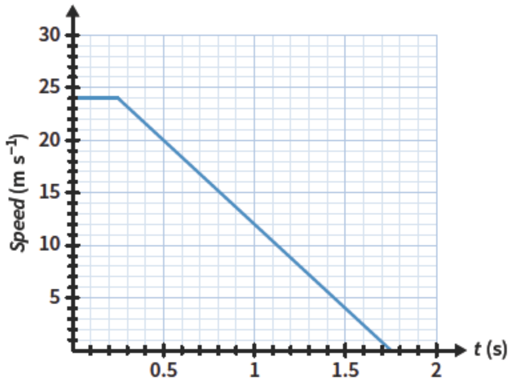
All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Take the value of *g* to be 9.8 m s^{-2} and ignore the effects of air resistance.

Use the following information to answer Questions 1 and 2.

Arcadio is riding his motorcycle of mass 280 kg when he is forced to brake suddenly to avoid an oncoming collision. He takes 0.25 s to react and then brakes with a constant braking force until he is stationary. His speed-time graph is shown to the right.



Question 1

Which one of the following is the best estimate of how far Arcadio travels before coming to rest, including the time he takes to react?

A 21 m **B** 24 m **C** 36 m **D** 42 m

Question 2

Which one of the following is closest to the magnitude of the braking force acting on Arcadio's motorcycle during the braking period?

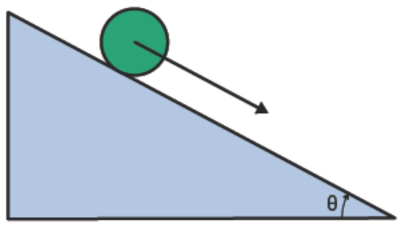
A 3.8 kN **B** 6.7 kN **C** 27 kN **D** 4.5 kN

Adapted from VCAA 2018 Physics Exam Section A Q6

Question 3

A ball is on an inclined frictionless plane as shown in the provided diagram.

Which one of the following statements about the motion of the ball as it rolls down the plane is correct?



A The ball travels at a constant speed.

B The momentum of the ball is conserved.

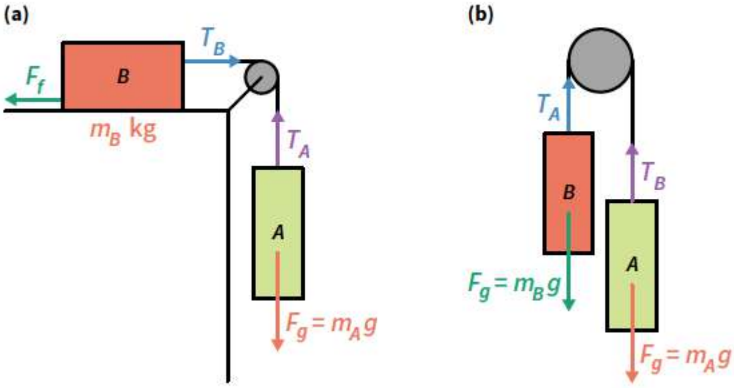
C The magnitude of the normal force is less than the force due to gravity.

D The ball is accelerating perpendicular to the plane.

Adapted from VCAA 2019 Physics Exam Section A Q12

Question 4

The provided diagrams show the forces acting in two separate frictionless pulley systems **(a)** and **(b)**.



Block *A* falls downwards at a constant speed in both systems. Which one of the following statements is correct?

A In **(a)**, m_A equals m_B.

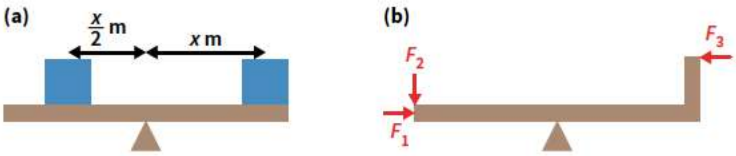
B In **(b)**, m_A equals m_B.

C In both systems, m_A is greater than m_B.

D In both systems, the acceleration of both blocks *A* and *B* does not depend on their mass.

Question 5

The provided diagrams show **(a)** two blocks of different masses resting on a seesaw and **(b)** three non-zero forces acting on an identical seesaw. Which one of the following statements must be true, assuming all parts of the see-saw are weightless?



A **(a)** cannot be in static equilibrium because the masses are different distances from the pivot point.

B **(b)** cannot be in static equilibrium because it cannot be in rotational equilibrium.

C Both **(a)** and **(b)** can be in static equilibrium for certain values of the unknowns.

D **(b)** will always be in static equilibrium because F_1 and F_3 are acting in opposite directions.

SECTION B

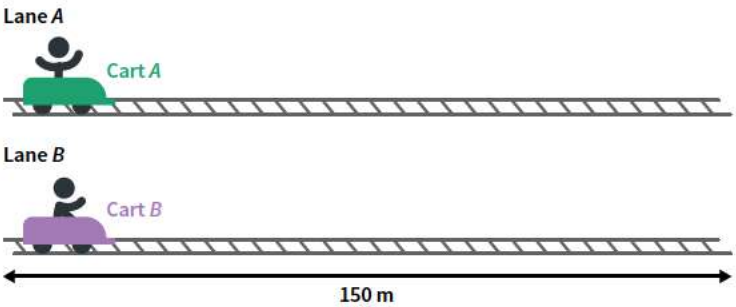
In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Take the value of g to be 9.8 m s^{-2} and ignore the effects of air resistance unless otherwise indicated.

Question 6 (8 MARKS)

A theme park is opening a new roller coaster ride. It features two tracks for two carts which travel at different speeds. Part of the ride consists of a flat section of length 150 m as shown in the provided diagram.



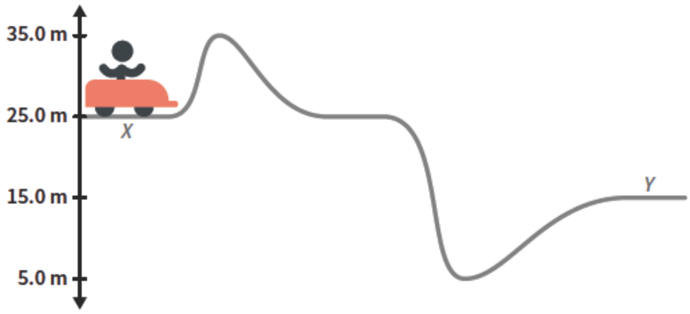
The cart in Lane *A* accelerates through the flat section at a constant rate for 5.50 seconds and has a velocity of 39.0 m s^{-1} when it reaches the end of the section.

a Calculate cart *A*'s speed at the start of the flat section. (2 MARKS)

b The ride's designers want to make this straight portion of track longer so that cart *A* and cart *B* will reach the end of it at the same time. They plan for cart *A* to travel through the section at a constant velocity of 24 m s^{-1}. Cart *B* will start 1.0 seconds after cart *A* leaves and will accelerate at 8.5 m s^{-2} for 4.0 seconds before maintaining a constant velocity.

Calculate how long the track would have to be for cart *B* to catch up to cart *A* at the end of the track. (4 MARKS)

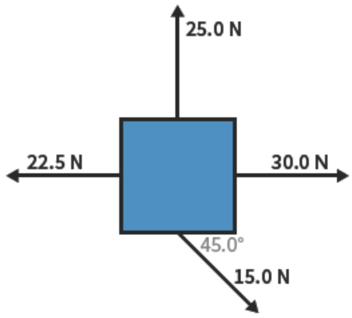
c Another cart enters the portion of track shown in the diagram below with a velocity of 15 m s^{-1}. The cart's motors provide no acceleration at any point along this part of the ride.



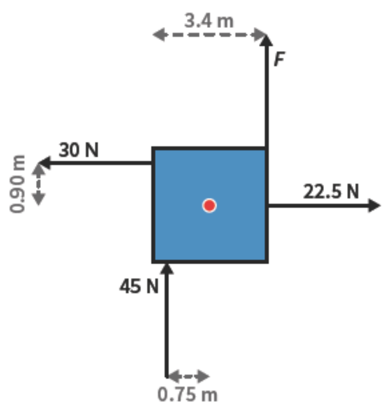
Calculate the final speed of the cart. Assume that the cart has enough kinetic energy to roll over the uphill sections shown. (2 MARKS)

Question 7 (5 MARKS)

a The provided diagram shows a series of forces acting on a block. Calculate the magnitude of the net force acting on the block and the angle it makes to the horizontal. (3 MARKS)



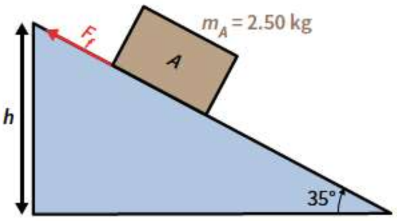
b The forces acting on the block have now changed.



Find the magnitude of the force labelled *F* in the provided diagram if the block is in rotational equilibrium. Assume that the block rotates about its centre (shown in red). (2 MARKS)

Question 8 (10 MARKS)

A distribution company is trialling a new conveyor system for their boxes as shown in the provided diagram. The boxes first slide down a rough inclined plane and then onto a smooth frictionless surface. A particular box *A* is currently sliding down the inclined plane, and has a mass of 2.50 kg.



a Calculate the magnitude of the normal force acting on box *A*. (2 MARKS)

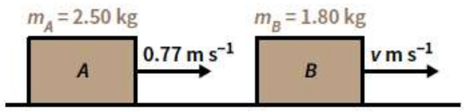
b Starting from rest, box *A* accelerates down the plane at a constant rate of 0.25 m s^{-2}. The friction force does 16 J of work over the distance it slides.

Calculate the magnitude of the friction force acting on the box. (2 MARKS)

c Show that the height *h* of the ramp is 0.68 m. (2 MARKS)

d Show that the magnitude of box *A*'s velocity when it reaches the bottom of the ramp is 0.77 m s^{-1}. (1 MARK)

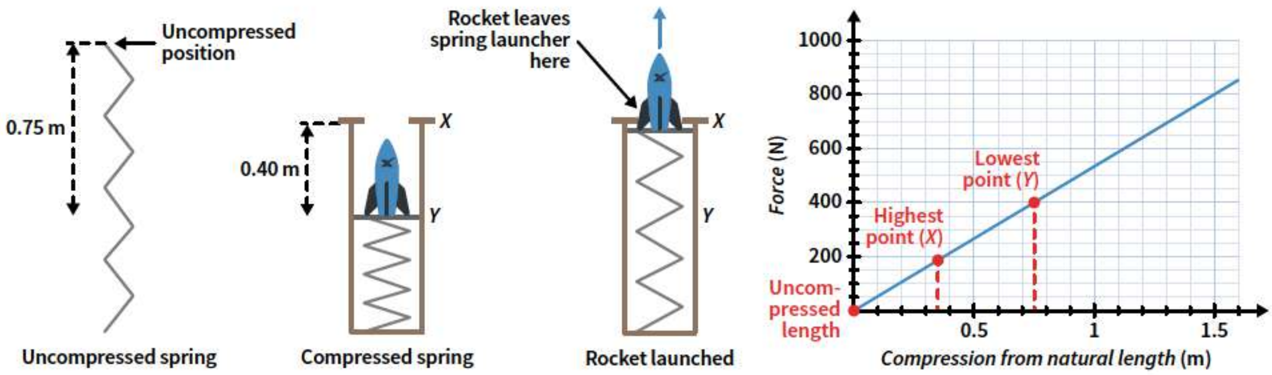
e Continuing to move at 0.77 m s^{-1}, box *A* collides with another box *B*, which has a mass of 1.80 kg.



Calculate the required magnitude of *v* so that after the collision the two boxes have a speed of 0.50 m s^{-1}. Assume that the two blocks remain in contact after the collision. (3 MARKS)

Question 9 (6 MARKS)

Elon Musk is currently trialling different methods of launch for his SpaceX program. One suggestion is to use springs instead of thrusters, so he is conducting a trial version with an 800 g model spacecraft. The spring launcher is shown in the included diagram. When the spring is released from *Y* and reaches *X*, it is held stationary, but is still partly compressed. Ignore the mass of the spring.



a Show that the spring constant, *k*, is equal to 5.33 × 10^2 N m^{-1}. (1 MARK)

b Show that the speed of the rocket when it leaves the launcher (at point *X*) is 17 m s^{-1}. (3 MARKS)

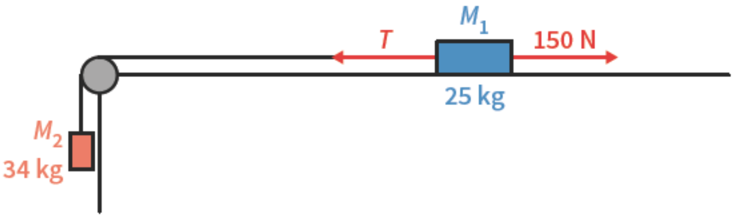
c Due to air resistance, the rocket only reaches a maximum height of 12.5 m. Calculate the percentage of energy given to the rocket by the spring launcher that the rocket loses to air resistance. (2 MARKS)

Adapted from 2018 VCAA NHT Exam Section B Q9

Find out more about the concepts behind this animation in Lesson 7C.

Question 10 (3 MARKS)

The provided diagram shows two masses, M_1 (25 kg) and M_2 (34 kg), connected by a rope that runs through a pulley. M_2 is accelerating downwards at 3.14 m s^{-2}.



Find the magnitude of the tension in the rope.

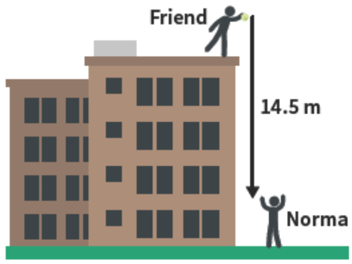
Question 11 (7 MARKS)

Norma is trying to catch a tennis ball at the highest speed she can. To do this she stands on flat ground and throws the ball up vertically as hard as she can. Her goal is to catch the ball (at the height she threw it from) when it has a speed of 18.0 m s^{-1}.

a What will be the maximum height the ball reaches with this final velocity? (2 MARKS)

b Norma's hardest throw only gives the ball an initial velocity of 15.0 m s^{-1} upwards. Explain why it is impossible for Norma to catch the ball at 18.0 m s^{-1}. (2 MARKS)

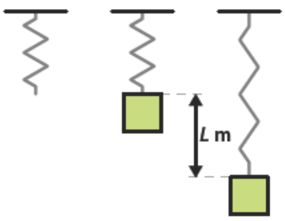
c Norma changes her plan and gets her friend to throw the ball vertically down to her from a building. Norma catches the ball at 18.0 m s^{-1} after it has fallen 14.5 m.



Calculate the amount of time for which the ball was in the air. (3 MARKS)

Question 12 (6 MARKS)

A 3.2 kg mass is suspended from a spring with a spring constant $k = 75$ N m^{-1}, as shown in the provided diagram. It is released from rest from the unstretched position of the spring and falls a distance of L m before momentarily coming to rest and bouncing back up again.



a Using this information, show that the value of L is 0.84 m. (1 MARK)

b Calculate the speed of the mass at its midpoint ($\Delta x = 0.42$ m). (2 MARKS)

c The mass oscillates up and down. Show that the extension of the spring at its equilibrium position is 0.42 m. (1 MARK)

d The value found in part **b** is the maximum speed the mass will reach as it falls. Use your answer from part **c** to explain why this is the case. (2 MARKS)

Adapted from 2015 VCAA Exam Section A Q6

1A Asking questions, identifying variables, and making predictions

Theory review questions

1 A

2 II; III; IV

3 **a** Dependent variable

b Controlled variable

c Independent variable

4 I-Quantitative; II-Qualitative; III-Qualitative; IV-Quantitative; V-Quantitative.

5 **a** Scientific model

b Scientific theory

c Scientific hypothesis

Exam-style questions

This lesson

6 **a** Volume setting (1 MARK)

Qualitative (1 MARK)

b Maximum distance that phone can be heard (1 MARK)

Quantitative (1 MARK)

c Message alert tone **OR** phone used **OR** listener **OR** environmental conditions (a large outdoor space) (1 MARK)

7 B (1 MARK)

8 A (1 MARK)

9 C (1 MARK)

1B Scientific conventions

Theory review questions

1 **a** 3. Trailing zeros are significant.

b 5. All non-leading zeros are significant.

c 4. Leading zeros are not significant.

d 1

e 6. Zeros between digits are always significant.

f 3

g 4

h 5

i 3

2 **a** 1.2×10^{-1}

b 6.0×10^{3}

c 3.0×10^{-8}

d 8.9×10^{6}

e 7.8×10^{-4}

f 6.37×10^{4}

3 **a** 44 (0 decimal places)

b 33.326 (3 decimal places)

c 73 (0 decimal places)

d 59.0 (1 decimal place)

e 875.1 (1 decimal place)

f 60.02 (2 decimal places)

4 **a** 9.1×10^{3} (2 significant figures)

b 3.3×10^{1} (2 significant figures)

c 3.69×10^{-2} (3 significant figures)

d 2.5×10^{7} (2 significant figures)

e 3.27×10^{4} (3 significant figures)

f 5×10^{3} (1 significant figure)

5 **a** $600 \text{ ms} = 600 \times 10^{-3} \text{ s} = 6.00 \times 10^{-1} \text{ s}$

b 6.4×10^{3} J

c $0.400 \text{ μg} = 0.400 \times 10^{-9} \text{ kg} = 4.00 \times 10^{-10} \text{ kg}$

d $23 \text{ MΩ} = 23 \times 10^{6} \text{ Ω} = 2.3 \times 10^{7} \text{ Ω}$

e $360 \text{ nm} = 360 \times 10^{-9} \text{ m} = 3.60 \times 10^{-7} \text{ m}$

f 7.0×10^{-12} A

6 I; IV; V; VIII; XIII

Exam-style questions

This lesson

7 $E = VQ = 6.00 \times 4.00$ (1 MARK)

$E = 24.0$ J (3 significant figures) (1 MARK)

8 0.135 km = 135 m

total distance = 135 + 63 = 198 m (3 significant figures) (1 MARK)

$speed = \frac{total\ distance}{time} = \frac{198}{67.0}$ (1 MARK)

$speed = 2.96 \text{ m s}^{-1}$ (3 significant figures) (1 MARK)

1C Collecting data

Theory review question

1 II; V; VII; VIII; X

Exam-style questions

This lesson

2 D (1 MARK)

See definition in theory.

3 C (1 MARK)

C is describing the uncertainty in the average of multiple measurements, not the true value.

4 D (1 MARK)

Systematic error refers to a consistent deviation in the measured results. When readings are repeated, assuming nothing else has been changed, they will still be affected by the same systematic error.

5 D (1 MARK)

Random errors will always be present because it is impossible to take a measurement with complete certainty.

6 C (1 MARK)

The reliability of an experiment is primarily tested through its repeatability and reproducibility. Option D is incorrect because reproducibility relates to precision. Even if an experiment is accurate when repeated by other experimenters, the initial experiment could have been inaccurate (making the results between experiments imprecise), and thus its results not reproduced.

7 D (1 MARK)

The range of Belle's results (2.40 V) is bigger than the range of Georgina's results (0.80 V), and therefore Belle's results are less precise.

8 B (1 MARK)

The uncertainty is the absolute value of the difference between the average result and the most extreme result. In this case, the average is 9.81, and $|9.81 - 9.75| = 0.06 \text{ m s}^{-2}$.

9 B (1 MARK)

Relative to the other students, Student B has points centred near the true value (accurate) and the points are all close together (precise).

10 D (1 MARK)

Relative to the other students, Student D has points that are not centred near the true value (inaccurate) and the points are all close together (precise).

11 D (1 MARK)

Relative to the other students, Student D has points that have an average position that is furthest away from the true value (least accurate).

12 C (1 MARK)

Relative to the other students, Student C has points centred near the true value (accurate) but that are not close together (imprecise).

13 B (1 MARK)

The uncertainty in a measuring device is half the smallest measuring increment. The smallest increment is 1 g, therefore the uncertainty is 0.5 g.

14 [Uncertainty in a measuring device is defined as half the smallest measuring increment.[1]][If the measuring increments are smaller, the uncertainty is also smaller.[2]]

- I have used the relevant theory: uncertainty in a measuring device.[1]
- I have explicitly addressed why a more precise measuring device has less uncertainty.[2]

15 [Accuracy refers to how well a measurement agrees with the 'true' value of a measurement.[1]][If a measuring device is not properly calibrated, this will introduce a systematic error that will shift measurements uniformly away from their 'true' value. Therefore, proper calibration can increase accuracy.[2]]

- I have used the relevant theory: accuracy.[1]
- I have used the relevant theory: systematic error.[2]

16 a Gen: $\frac{4.0+4.5+3.6+4.3}{4} = 4.1 \text{ V}$ (1 MARK)

Jana: $\frac{3.8+4.1+4.2+3.9}{4} = 4.0 \text{ V}$ (1 MARK)

b Gen: 4.5 − 3.6 = 0.9 V (1 MARK)

Jana: 4.2 − 3.8 = 0.4 V (1 MARK)

c [Gen's data is more accurate than Jana's data[1]][as Gen's average of 4.1 V is closer to the true voltage of 4.2 V than Jana's average of 4.0 V.[2]]

- I have explicitly addressed which person's data is more accurate.[1]
- I have used the relevant theory: accuracy.[2]
- I have related my answer to the context of the question.

d [Jana's data is more precise than Gen's data[1]][as the range of Jana's results (0.4 V) is smaller than the range of Gen's results (0.9 V).[2]]

- I have explicitly addressed which person's data is more precise.[1]
- I have used the relevant theory: precision.[2]
- I have related my answer to the context of the question.

17 III; V; VI; VII; IX; X (6 MARKS)

III, V, and VII are changing a controlled variable. VI is experimenter bias and data manipulation. IX is data manipulation – The exclusion of data points must always be justified in the analysis. X is concluding that the dependent variable causes a change in the independent variable.

1D Representing and analysing data

Theory review questions

1 A. The independent variable should be plotted on the horizontal axis and the dependent variable should be plotted on the vertical axis.

2 B. The uncertainty bars indicate the area where the true value might be located.

3 II; III. P vs V^2 corresponds to a linear graph with a gradient of $\frac{1}{R}$. $\sqrt{P}$ vs V corresponds to a linear graph with a gradient of $\frac{1}{\sqrt{R}}$.

1D

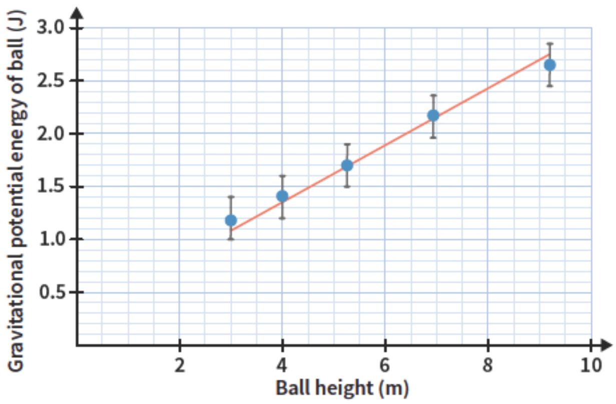
Exam-style questions

This lesson

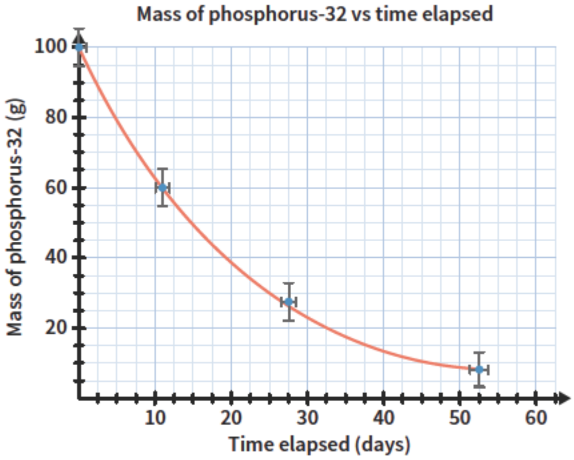
4 a [A line of best fit is valid if a straight line can be drawn through the uncertainty bars of all points.[1]] [Therefore, vertical uncertainty bars of equal size must be drawn on each data point, and then a straight line must be drawn through all of the uncertainty bars.[2]]

- I have used the relevant theory: lines of best fit.[1]
- I have used the relevant theory: uncertainty bars.[2]

b The graph can have a line of best fit. (1 MARK)

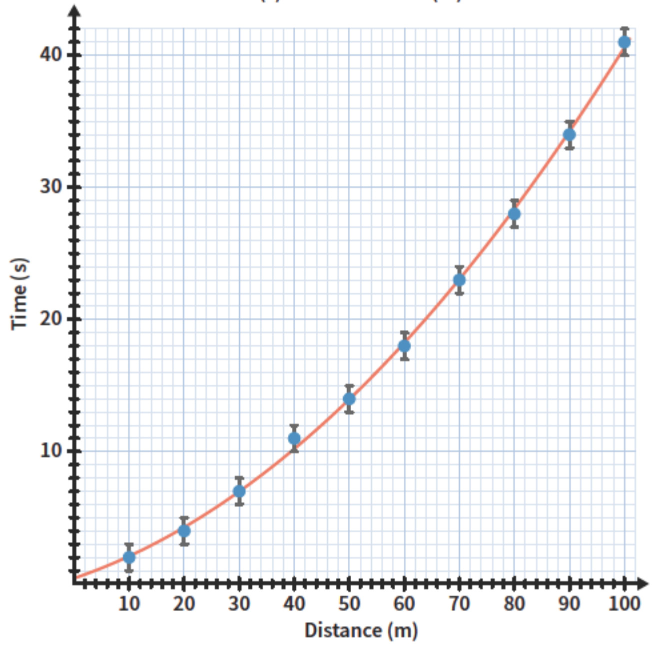


5 Mass of phosphorus-32 vs time elapsed



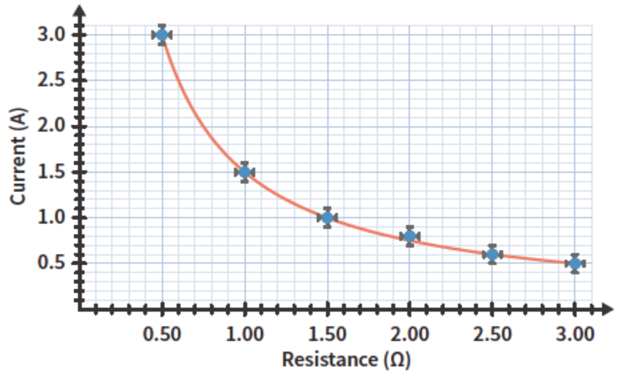
- I have labelled the horizontal axis with the independent variable and included correct units.
- I have labelled the vertical axis with the dependent variable and included correct units.
- I have included an appropriate and consistent scale on both axes.
- I have plotted each point of data: (0, 100), (11, 60), (27, 28), (52, 8).
- I have drawn correctly sized uncertainty bars: (horizontal: ±1 day, vertical: ±5 g).
- I have drawn a curve of best fit which passes through all uncertainty bars.

6 Time (s) versus distance (m)



- I have labelled the horizontal axis with the independent variable and included correct units.
- I have labelled the vertical axis with the dependent variable and included correct units.
- I have included an appropriate and consistent scale on both axes.
- I have plotted each point of data: (10, 2), (20, 4), (30, 7), (40, 11), (50, 14), (60, 18), (70, 23), (80, 28), (90, 34), (100, 41).
- I have drawn correctly sized uncertainty bars: (vertical: ±1 s).
- I have drawn a curve of best fit which passes through all uncertainty bars.

7 a Current versus resistance



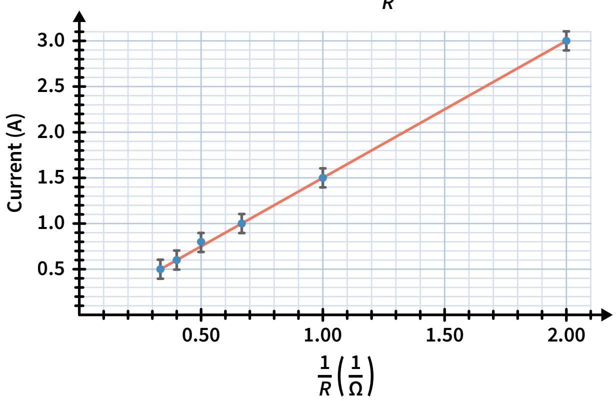
- I have labelled the horizontal axis with the independent variable and included correct units.
- I have labelled the vertical axis with the dependent variable and included correct units.
- I have included an appropriate and consistent scale on both axes.
- I have plotted each point of data: (0.50, 3.0), (1.00, 1.5), (1.50, 1.0), (2.00, 0.8), (2.50, 0.6), and (3.00, 0.5).

I have drawn correctly sized uncertainty bars: (horizontal: ±0.05 Ω, vertical: ±0.1 A).

I have drawn a curve of best fit which passes through all uncertainty bars.

b

Current versus $\frac{1}{R}$



I have labelled the horizontal axis with the independent variable and included correct units.

I have labelled the vertical axis with the dependent variable and included correct units.

I have included an appropriate and consistent scale on both axes.

I have calculated and plotted each point of data: (2.00, 3.0), (1.00, 1.5), (0.67, 1.0), (0.50, 0.8), (0.40, 0.6), (0.33, 0.5).

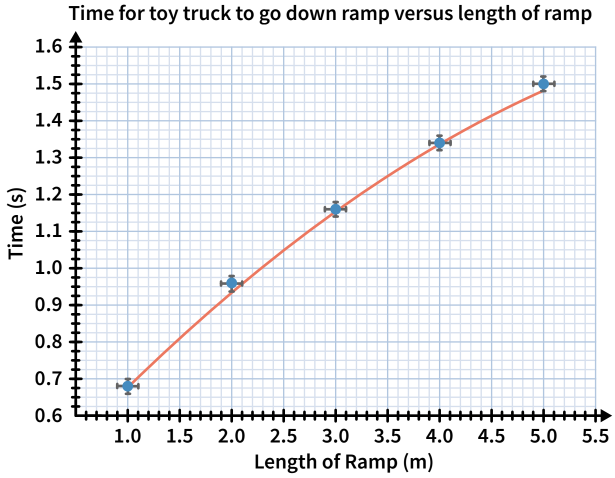
I have drawn correctly sized uncertainty bars: (vertical: ±0.1 A).

I have drawn a line of best fit which passes through all uncertainty bars.

c Maneesha is correct that $I \propto \frac{1}{R}$ (since a straight line fits the linearised data). (1 MARK)

8 a

Time for toy truck to go down ramp versus length of ramp



I have labelled the horizontal axis with the independent variable and included correct units.

I have labelled the vertical axis with the dependent variable and included correct units.

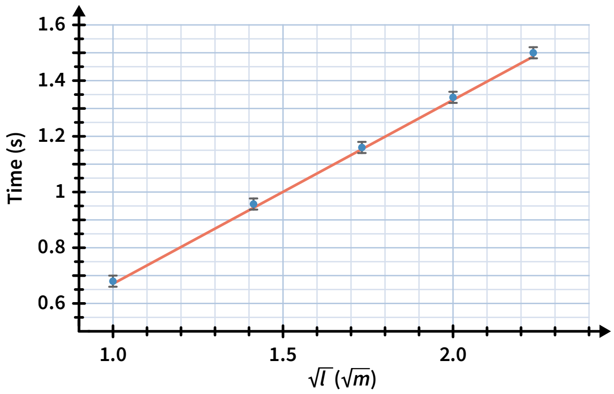
I have included an appropriate and consistent scale on both axes.

I have plotted each point of data: (1.0, 0.68), (2.0, 0.96), (3.0, 1.16), (4.0, 1.34), (5.0, 1.50).

I have drawn correctly sized uncertainty bars: (horizontal: ±0.1 m, vertical: ±0.02 s).

I have drawn a curve of best fit which passes through all uncertainty bars.

b Time for toy truck to go down ramp vs square root of ramp length



I have labelled the horizontal axis with the independent variable and included correct units.

I have labelled the vertical axis with the dependent variable and included correct units.

I have included an appropriate and consistent scale on both axes.

I have calculated and plotted each point of data: (1.0, 0.68), (1.4, 0.96), (1.7, 1.16), (2.0, 1.34), (2.2, 1.50).

I have drawn correctly sized uncertainty bars: (vertical: ±0.02 s).

I have drawn a line of best fit which passes through all uncertainty bars.

c [Aditya is correct in saying that $t \propto \sqrt{l}$[1]][as the graph in part **b** has a line of best fit.[2]]

I have explicitly addressed whether Aditya's hypothesis is supported by the data.[1]

I have used the provided data (the graph in part **b**) in my answer.[2]

1E Gradients of lines of best fit

Theory review questions

1 D. Gradient always represents $\frac{\textit{change in vertical axis variable}}{\textit{change in horizontal axis variable}}$.

2 A. $\frac{\textit{vertical axis unit}}{\textit{horizontal axis unit}} = \frac{\text{kg m s}^{-1}}{\text{s}} = \text{kg m s}^{-2}$

3 A. Rearranging the equation provided gives $\frac{\Delta p}{\Delta t} = F$.

4 Q and S. We must choose two points that are on the line of best fit. The effect of any errors when reading the coordinates will be minimised (yielding the most accurate results) by choosing points that are furthest apart.

Exam-style questions

This lesson

5 a Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{9.0 - 3.0}{3.0 - 1.0}$ (1 MARK)

$gradient = 3.0 \text{ m s}^{-2}$ (1 MARK)

b $gradient = \frac{rise}{run} = \frac{v^2}{d}$

The original equation is $v^2 = 2ad$ $\therefore \frac{v^2}{d} = 2a$ $\therefore gradient = 2a$ (1 MARK)

$2a = 3.0$ $\therefore a = 1.5 \text{ m s}^{-2}$ (1 MARK)

6 Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0.200 - 0.050}{4.0 - 1.0}$ (1 MARK)

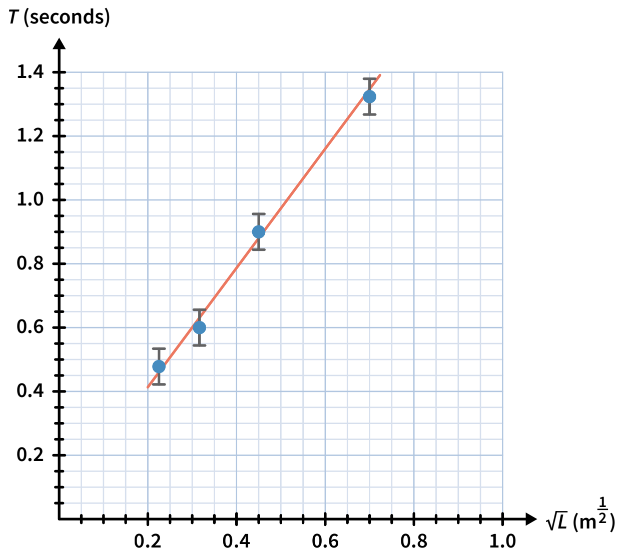
$gradient = 0.050 \text{ A V}^{-1}$ (1 MARK)

$gradient = \frac{rise}{run} = \frac{I}{V}$

The original equation is $I = \frac{V}{R}$ $\therefore \frac{I}{V} = \frac{1}{R}$ $\therefore gradient = \frac{1}{R}$ (1 MARK)

$\frac{1}{R} = 0.050$ $\therefore R = 20$ ohms or V A^{-1} (1 MARK)

7 a



I have drawn a line of best fit that passes through all uncertainty bars.

I have drawn a line that does not extend significantly beyond the region of the data points.

b Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.35 - 0.45}{0.70 - 0.22}$ (1 MARK)

$gradient = 1.88 \text{ s m}^{-\frac{1}{2}}$ (1 MARK)

$gradient = \frac{rise}{run} = \frac{T}{\sqrt{L}}$

The original equation is $T = 2\pi\sqrt{\frac{L}{g}}$ $\therefore \frac{T}{\sqrt{L}} = \frac{2\pi}{\sqrt{g}}$

$\therefore gradient = \frac{2\pi}{\sqrt{g}}$ (1 MARK)

$1.88 = \frac{2\pi}{\sqrt{g}}$ $\therefore g = 11 \text{ m s}^{-2}$ (1 MARK)

Depending on the line of best fit drawn, answers between 9.0 m s^{-2} and 14 m s^{-2} are acceptable.

Chapter 1 Review

Section A

1 C. Option A defines a hypothesis. Unlike what is suggested in option B, models have other uses, such as making predictions. Option D defines a scientific theory.

2 B. Convert 1.2×10^9 to 0.12×10^{10} so that both terms are multiplied by the same power of 10.

$5.124 \times 10^{10} - 0.12 \times 10^{10} = 5.004 \times 10^{10} = 5.00 \times 10^{10}$

As the term with the fewest decimal places only has two decimal places, so should the final answer.

3 A. Uncertainty is equal to half the measuring device's smallest increment.

$\frac{1}{2} \times 1 \text{ mA} = 0.5 \text{ mA}$

4 D. Point *S* represents an outlier that is known to have been introduced by personal error and can be discarded.

5 A

$gradient = \frac{change\ in\ vertical\ axis}{change\ in\ horizontal\ axis} = \frac{\Delta v^2}{\Delta h}$

$gh = \frac{1}{2}v^2$ $\therefore 2g = \frac{v^2}{h} = gradient$

Section B

6 a [This statement is an example of a hypothesis.[1]][It makes a prediction about the relationship between smoking and beard growth that can be tested.[2]]

I have explicitly addressed whether the statement is a scientific model, theory, or hypothesis.[1]

I have used the relevant theory: the definition of a hypothesis.[2]

b [This study cannot be considered valid.[1]][As the scientists were provided financial incentive to produce certain results,[2]][this very likely introduced observer bias into the method (or resulted in poor experimental design or analysis), invalidating the experiment.[3]]

I have explicitly addressed the validity of the study.[1]

I have explicitly addressed the financial incentives given to the scientists.[2]

I have used the relevant theory: validity of experimental design.[3]

7 a Independent: mass of metal sample (1 MARK)

Dependent: energy used by bunsen burner (1 MARK)

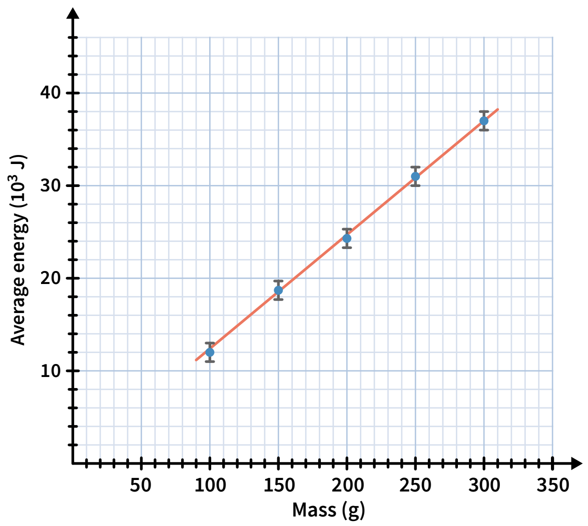
Control: bunsen burner/rate sample is heated **OR** temperature sample is heated to **OR** temperature sample is heated from **OR** number of times sample is heated (1 MARK)

b [This experiment is reasonably repeatable as each set of measurements is consistently precise.[1]][However, repeatability could be improved by using a better method of measuring the thermal energy absorbed by the metal.[2]]

I have explicitly addressed the repeatability of the experiment.[1]

I have used the relevant theory: repeatability.[2]

c



I have correctly labelled the horizontal axis and included correct units.

I have correctly labelled the vertical axis and included correct units.

I have included an appropriate and consistent scale on the horizontal axis.

I have included an appropriate and consistent scale on the vertical axis.

I have plotted each point of data: (100, 12.0), (150, 18.7), (200, 24.3), (250, 31.0), (300, 37.0).

I have drawn correctly sized uncertainty bars: (vertical: $\pm 1 \times 10^3$ J).

I have drawn a line of best fit which passes through all uncertainty bars.

d [Accuracy measures how close the average of a set of data is to the predicted value and precision measures how consistently the experimental data was recorded.[1]][The data for the 150 g sample is more accurate as the average is closer to the true value.[2]][The data for the 150 g sample is also more precise as the range of data taken is smaller.[3]]

I have used the relevant theory: what precision and accuracy measures.[1]

I have explicitly addressed the difference in accuracy of the two data sets.[2]

I have explicitly addressed the difference in precision of the two data sets.[3]

8 a Quantitative data (1 MARK)

b Systematic error (1 MARK)

c Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{120 - 46}{13 - 5.0}$ (1 MARK)

$gradient = 9.3\ \text{N kg}^{-1}$ or m s^{-2} (1 MARK)

Answers between $9.0\ \text{N kg}^{-1}$ and $9.4\ \text{N kg}^{-1}$ are acceptable.

d [Enya's experiment is not reproducible.[1]][This is because when the experiment was repeated by different experimenters in different lab conditions, with the same method and materials, the results were not consistent.[2]]

I have explicitly addressed the reproducibility of Enya's experiment.[1]

I have used the relevant theory: reproducibility.[2]

2A What is temperature?

Theory review questions

1 average; translational kinetic

2 **a** A

b B

3 gas; greatest; solid; least

4 B. According to the kinetic theory of matter, atoms and molecules are always in motion (but they move more as temperature increases).

5 A

6 C. The size of 1°C is the same as the size of 1 K, so a change in temperature will have the same numerical value when measured with either unit.

Deconstructed exam-style question

7 **a** D

b B

c [Initially, the particles in the cup of coffee have greater average translational kinetic energy than in her hand because the coffee is at a greater temperature.[1]][As the cup warms the hand, the average translational kinetic energy of the particles in the cup of coffee decreases and the average translational kinetic energy of the particles in her hand increases.[2]][When thermal equilibrium is reached, the average translational kinetic energy of the particles in each system will be equal.[3]]

- I have explicitly addressed the average translational kinetic energies at the start.[1]
- I have explicitly addressed the average translational kinetic energies as the coffee warms her hand.[2]
- I have explicitly addressed the average translational kinetic energies at thermal equilibrium.[3]

Exam-style questions

This lesson

8 [No.[1]][Increasing the temperature means increasing the average translational kinetic energy associated with the random motion of the atoms/molecules in a system.[2]][This is one of the types of energy that make up internal energy, so internal energy must also increase.[3]]

- I have explicitly addressed whether the internal energy can remain constant when the temperature increases.[1]
- I have used the relevant theory: temperature as a measure of average translational kinetic energy of particles.[2]
- I have used the relevant theory: what makes up internal energy.[3]

9 735 K = (735 − 273.15)°C = 462°C (1 MARK)

10 **a** −170°C = (−170 + 273.15) K = 103 K (1 MARK)

b ΔT = 450°C − (−170°C) = 620°C = 620 K (1 MARK)

11 [Temperature is a measure of the average translational kinetic energy of the random disordered motion of the particles in a system.[1]] [Hence, the average translational kinetic energy of the atoms and molecules will be greater during the day than during the night.[2]]

- I have used the relevant theory: temperature as a measure of average translational kinetic energy of particles.[1]
- I have explicitly addressed the kinetic energy of atoms and molecules during the day compared with during the night.[2]

12 [Particles in water (a liquid) are free to move around each other, whereas particles in ice (a solid) are stuck together,[1]][which explains the macroscopic properties of liquids being able to change shape and solids having a fixed shape.[2]][Hence water can flow as a thin stream into a bottle and then take the bottle's shape, whereas ice cannot.[3]]

- I have used the relevant theory: the kinetic theory of matter for solids and liquids.[1]
- I have used the relevant theory: the macroscopic properties of solids and liquids.[2]
- I have explicitly addressed the properties of water that allow it to fill the bottle easily.[3]

13 [Archie is incorrect.[1]][Temperature is a measure of the average translational kinetic energy of the random disordered motion of the atoms and molecules in a system.[2]][The collective change in speed of the basketball and its particles as a result of its macroscopic movement is not related to the particles' random disordered motion.[3]]

- I have explicitly addressed whether Archie is correct.[1]
- I have used the relevant theory: temperature as a measure of average translational kinetic energy particles.[2]
- I have related my answer the the context of the question.[3]

14 **a** The internal energy of the water in the Olympic pool would be greater than the internal energy of water in the backyard pool. (1 MARK)

This is because the Olympic pool has a greater volume.

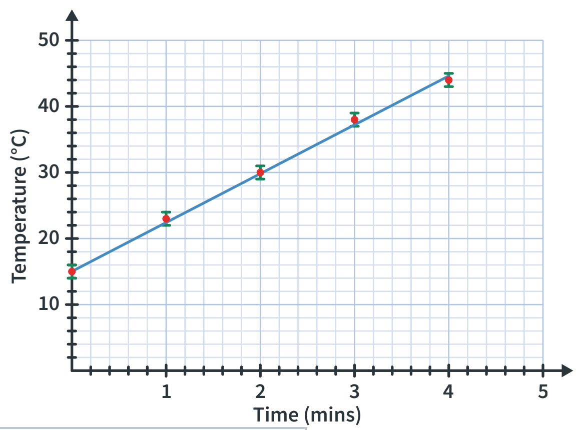
b The average translational kinetic energy of the water molecules in the backyard pool would be the same as the average translational kinetic energy of the water molecules in the Olympic pool. (1 MARK)

This is because the pools are at the same temperature.

Key science skills

15 **a** Uncertainty = $\frac{1}{2}$ × smallest division on scale = $\frac{1}{2}$ × 2°C = 1°C (1 MARK)

b



- I have drawn time on the horizontal axis.
- I have drawn temperature on the vertical axis.
- I have used an appropriate and consistent scale so the data takes up at least half of each axis.
- I have plotted each point of data.
- I have included correct uncertainty bars.
- I have drawn a line of best fit that passes through all the uncertainty bars.

2B How does thermal energy move?

Theory review questions

1 B. When systems are in thermal equilibrium, there is no net flow of heat between them.

2

	Relies on particle vibrations or collisions	Matter travels with the heat	Works well through air
Conduction	✓		
Convection		✓	✓
Thermal radiation	✓		✓

3 temperatures; in contact; heat; internal energy

Although temperature is related to internal energy, temperature (not internal energy) determines the flow of thermal energy.

“Coldness” or “cold” is not something that physically exists or is transferred between systems.

Heat does not describe energy that an object has; it describes the energy that is flowing between systems.

4 **a** C. Any temperature below 30°C will feel cold to Selina.

b A. If the metallic ball is better at cooling things down, it is a better thermal conductor. Therefore, it will also be better than the rubber ball at conducting thermal energy into Selina’s palm.

5 energy; heat; insulators

Heat does not describe energy that an object has; it describes the energy that is flowing between systems.

6 B. Within a fluid, convection is the most effective form of heat transfer.

7 B. Heat is a flow of energy and it does not always rise, but hot fluids rise during natural convection.

8 A. Metals are good conductors.

9 A. Conduction is independent of gravity so the results of Experiment 4 will be the same as those of Experiment 3. Conduction is equally effective regardless of whether the heat flows upwards or downwards.

10 **a** C

b A

11 D

Deconstructed exam-style question

12 **a** D **b** A

c [Sabrina is correct.[1]][As the heated fluid will be on top, it will not move since hotter fluid only rises above colder fluid.[2]][As convection requires movement of fluid, convection cells will not be able to form.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: hotter fluid rises above colder fluid.[2]
- I have used the relevant theory: requirements for convection.[3]

Exam-style questions

This lesson

13 B (1 MARK) **14** C (1 MARK)

15 B (1 MARK)
Rate of conduction is proportional to temperature difference.
$1.5 \times 100 = 150 \text{ J s}^{-1}$.

16 D (1 MARK)
Convection is when heat transfer occurs as a result of the movement of matter.

17 C (1 MARK)
It is impossible to tell because the balls are different sizes, and the rate of conduction depends on the surface area as well as temperature and material.

18 [Zev’s head is hotter than the ice pack and the two are in contact, so the heat will flow from his head to the ice pack[1]][through conduction.[2]][The particles that make up Zev’s head will transfer translational kinetic energy to the particles that make up the ice pack by colliding with them, increasing the ice pack’s internal energy.[3]]

- I have used the relevant theory: conditions for conduction.[1]
- I have explicitly addressed the kind of heat transfer taking place.[2]
- I have used the relevant theory: the mechanism of conduction.[3]

19 **a** Yes (1 MARK)
Thermal radiation is the primary form of heat transfer between the fire and Jim. Radiation does not require matter, so he will still feel a similar amount of warmth.

b Convection (1 MARK)
The hot air surrounding the fire rises due to its lower density, helping heat anything above the fire, but not to its side.
This is convection.

20 **a** Aluminium (1 MARK)
Pure metals are good thermal conductors.

b [Plastic should be used[1]][as it is a better insulator.[2]][This reduces the rate of heat flow compared to a conductor like aluminium.[3]]

- I have explicitly addressed whether plastic or aluminium should be used for the piping.[1]
- I have referenced that plastic is a good insulator.[2]
- I have used the relevant theory: insulators conduct heat poorly.[3]

21 $\Delta T_i = T_{plate} - T_{mitt}$ $\therefore \Delta T_i = 340 - 300$ $\therefore \Delta T_i = 40\ K$

Rate of heat flow halved and $\frac{Q}{t} \propto \Delta T$ $\therefore \Delta T_f = \frac{1}{2} \times \Delta T_i = \frac{1}{2} \times 40$ (1 MARK)

$\Delta T_f = 20$ K (1 MARK)

22 a Hotter (1 MARK)
Net thermal energy flows from hotter objects to colder objects, increasing the colder objects' internal energy.

b [Objects in thermal equilibrium are at the same temperature ($\Delta T = 0$).[1]][From the relation $\frac{Q}{t} \propto \Delta T$, this means $\frac{Q}{t}$ (the rate of heat flow due to conduction), must also be zero.[2]]

- I have used the relevant theory: the relationship between thermal equilibrium and temperature.[1]
- I have explicitly addressed the relevant relation that shows there will be no net flow of heat.[2]

23 a [The conduction occurs through physical contact with the air.[1]][A greater surface area means a higher amount of contact,[2]][which increases the rate of conduction with the air and cools the fins quicker.[3]]

- I have used the relevant theory: conditions for conduction.[1]
- I have referenced the fins' high area of contact with the air.[2]
- I have explicitly addressed the purpose of having a high surface area.[3]

b [The fins transfer the heat through conduction to the air.[1]][The fan[2]][then blows away this heated air, which is forced convection.[3]]

- I have referenced how the heat is transferred from the fins to the air.[1]
- I have explicitly addressed the role of the fan.[2]
- I have referenced how the fan transfers heat away from the fins.[3]

Previous lessons

24 [Particles in a solid are able to vibrate only,[1]][and do not move around. This is different to[2]][particles in liquids and gases, which are free to move around each other.[3]]

- I have used the relevant theory: movement of particles in a solid.[1]
- I have explicitly addressed what is unique about the movement of particles in solids compared to fluids.[2]
- I have used the relevant theory: movement of particles in fluids.[3]

This content was covered in Lesson 2A.

Key science skills

25 a 3 (1 MARK)
When adding values, we use the number of decimal places of the value with the fewest number of decimal places. That is 0.3 + 5.7 + 4.502 = 10.502 but we take 10.5 (one decimal place) because 0.3 and 5.7 have only one decimal place.

b 2 (1 MARK)
When multiplying numbers, we use the number of significant figures of the value with the fewest significant figures. Since one of the numbers (time) has only two significant figures, we can have only two significant figures for the answer. We get 10.502 × 5.0 = 53.

2C How heat affects temperature

Theory review questions

1 a 2000 J. $Q = mc\Delta T$ so if all else is equal, doubling ΔT means doubling Q.

b 3000 J. $Q = mc\Delta T$ so if all else is equal, tripling m means tripling Q.

2 a X. $\Delta T = \frac{Q}{mc}$ so if all else is equal, ΔT is greater for materials with a lower c.

b X. Same explanation as part **a**.

c Y. $Q = mc\Delta T$ so if all else is equal, Q is greater for materials with a greater c.

d Y. Same explanation as part **c**.

3 B. On a graph of T vs Q, a lower gradient represents a higher specific heat capacity since $c \propto \frac{Q}{\Delta T}$.

4 a Q to R

b T to S

c R to S

5 B

6 B. The energy is stored as potential energy as the particles overcome the intermolecular bonds between them.

7 A. The potential energy decreases as the intermolecular bonds force the particles into a more ordered structure. This energy is latent heat being released.

8 C. Only the potential energy of the particles changes during a change of state. The average translational kinetic energy of the particles does not change.

9 conduction; Z; X; Y.

Deconstructed exam-style question

10 **a** C

b B. Use $Q = mc\Delta T$ with appropriate unit conversions. ΔT is negative $(0 - 12 = -12\text{ K})$ because the water decreases in temperature. Therefore Q is also negative, which corresponds to a release of heat.

c D. Use $Q = mL$ with appropriate unit conversions.

d A. Use $Q = mc\Delta T$ with appropriate unit conversions and $\Delta T = T_f - 0$. ΔT is negative (T_f is negative).

e $Q_{water} = 0.100 \times 4.2 \times 10^3 \times (0 - 12) = -5.04 \times 10^3\text{ J}$ (1 MARK)

$Q_{Lf} = -0.100 \times 3.34 \times 10^5 = -3.34 \times 10^4\text{ J}$ (1 MARK)

$Q_{ice} = 0.100 \times 2.1 \times 10^3 \times (T_f - 0) = 2.1 \times 10^2 \times T_f$ (1 MARK)

$Q_{total} = Q_{water} + Q_{Lf} + Q_{ice} - 40 \times 10^3$
$= -5.04 \times 10^3 - 3.34 \times 10^4 + 2.1 \times 10^2 \times T_f$

$T_f = -7°\text{C}$ (1 MARK)

Exam-style questions

This lesson

11 $Q = mc\Delta T = 0.300 \times 7.2 \times 10^2 \times 4.0$ (1 MARK)

$Q = 8.6 \times 10^2\text{ J}$ (1 MARK)

12 $Q = mc\Delta T\ \therefore 5500 = 0.015 \times 450 \times \Delta T$ (1 MARK)

$\Delta T = 815\text{ K or °C}$ (1 MARK)

13 **a** For a gas condensing to a liquid, use the latent heat of vaporisation.

$Q = mL_v = 1.5 \times 1.1 \times 10^5$ (1 MARK)

$Q = 1.65 \times 10^5 = 1.7 \times 10^5\text{ J}$ released (1 MARK)

b The total heat released is the sum of the latent heat of vaporisation (while condensing) and the heat released while the liquid cools.

$Q_{total} = Q_{Lv} + Q_{liquid}\ \therefore 2.0 \times 10^5 = 1.65 \times 10^5 + Q_{liquid}$ (1 MARK)

$Q_{liquid} = 0.3 \times 10^5 = 3 \times 10^4\text{ J}$ released as the liquid cools (1 MARK)

14 [Xi is incorrect and Ruth is correct.[1]][The potential energy portion of the internal energy has increased as the solid melts to a liquid.[2]][The temperature has not increased because the translational kinetic energy portion of the internal energy has not changed.[3]]

- I have explicitly addressed whether each statement is correct.[1]
- I have used the relevant theory: latent heat corresponds to a change in potential energy.[2]
- I have used the relevant theory: why temperature does not change when a substance melts.[3]

15 **a** Use any two points on this section of the graph to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{40 - 0}{(25 - 0) \times 10^3}$ (1 MARK)

$gradient = 1.6 \times 10^{-3}\text{ K J}^{-1}$ (1 MARK)

b Consider the section of graph corresponding to solid lead.

For solid lead: $gradient = \frac{rise}{run} = \frac{\Delta T}{Q}$

The equation relating Q and ΔT is $Q = mc\Delta T\ \therefore gradient = \frac{1}{mc}$ (1 MARK)

$1.6 \times 10^{-3} = \frac{1}{5.0 \times c}$ (1 MARK)

$c = 125 = 1.3 \times 10^2\text{ J kg}^{-1}\text{ K}^{-1}$ (1 MARK)

c The heat absorbed when 5.0 kg of lead melts is given by the heat input for the flat section of the graph.

$Q_{Lf} = (150 - 25) \times 10^3 = 1.25 \times 10^5\text{ J}$ (1 MARK)

$Q_{Lf} = mL_f\ \therefore 1.25 \times 10^5 = 5.0 \times L_f$

$L_f = 2.5 \times 10^4\text{ J kg}^{-1}$ (1 MARK)

16 $Q_{Lf} = mL_f = 0.9 \times 3.3 \times 10^5 = 2.97 \times 10^5\text{ J}$ (1 MARK)

$Q_{total} = Q_{Lf} + Q_{water}$

$4.0 \times 10^5 = 2.97 \times 10^5 + 0.90 \times 4.2 \times 10^3 \times (T_f - 0)$ (1 MARK)

$T_f = 27°\text{C}$ (1 MARK)

17 The latent heat of vaporisation released by the steam as it condenses is transferred to the glass.

$Q_{Lv} = Q_{glass}\ \therefore (mL_v)_{steam} = (mc\Delta T)_{glass}$ (1 MARK)

$0.050 \times 2.3 \times 10^6 = 4.0 \times 840 \times \Delta T$ (1 MARK)

$\Delta T = 34\text{ K or °C}$ (1 MARK)

18 Consider the 1.2 kg of water as it cools:

$Q_{cooling} = mc\Delta T = 1.2 \times 4.2 \times 10^3 \times (T_f - 20)$ (1 MARK)

Consider the 200 g of ice as it melts:

$Q_{Lf} = mL_f = 0.200 \times 3.3 \times 10^5 = 6.6 \times 10^4\text{ J}$ (1 MARK)

Consider the 200g of melted ice (now water) as it warms:

$Q_{warming} = mc\Delta T = 0.200 \times 4.2 \times 10^3 \times (T_f - 0)$ (1 MARK)

The ice and the water must have the same final temperature. The sum of the heat released by the water (which is a negative value) and the total heat absorbed by the ice must be zero.

$1.2 \times 4.2 \times 10^3 \times (T_f - 20) + 6.6 \times 10^4 + 0.200 \times 4.2 \times 10^3 \times (T_f - 0) = 0$ (1 MARK)

$T_f = 5.92 = 5.9°\text{C}$ (1 MARK)

19 [Rubbing alcohol evaporates more quickly than water[1]][because of rubbing alcohol's lower values for specific latent heat of vaporisation and boiling point compared with water.[2]][This means that higher energy particles escape from the liquid at a greater rate, which causes its temperature to drop at a greater rate and feel cooler to the touch.[3]]

I have explicitly addressed the reason that rubbing alcohol feels colder than water.[1]

I have referenced the data from the table.[2]

I have used the relevant theory: the process of evaporative cooling.[3]

Previous lessons

20 $-145°C = -145 + 273.15 = 128.15 = 128$ K (1 MARK)

This content was covered in Lesson 2A.

21 $\frac{\Delta T_f}{\Delta T_i} = \frac{100}{400} = \frac{1}{4}$ $\therefore \Delta T_f = \frac{1}{4}\Delta T_i$ (1 MARK)

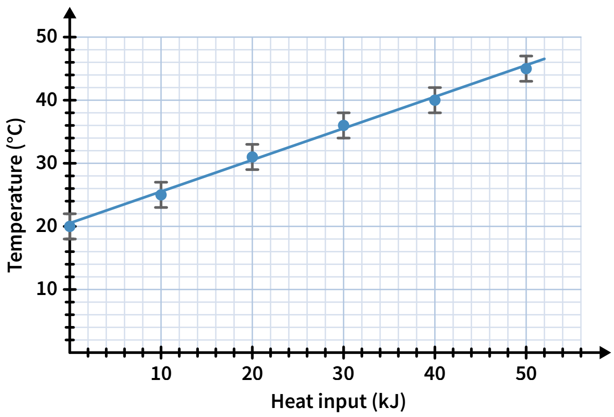
The difference in temperature changed by a factor of $\frac{1}{4}$ and $\frac{Q}{\Delta t} \propto \Delta T$

$\therefore$ the rate of heat transfer has also changed by a factor of $\frac{1}{4}$. (1 MARK)

This content was covered in Lesson 2B.

Key science skills

22 a



I have labelled both axes and included correct units.

I have included an appropriate and consistent scale on both axes.

I have plotted each data point.

I have drawn correctly sized uncertainty bars.

I have drawn a straight line of best fit which passes through all uncertainty bars.

b Use any two points on the line of best fit to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{44 - 22}{(47 - 3) \times 10^3} = 5.0 \times 10^{-4}\ °C\ J^{-1}$ (1 MARK)

$gradient = \frac{rise}{run} = \frac{\Delta T}{Q}$

The equation relating Q and ΔT is $Q = mc\Delta T$ $\therefore gradient = \frac{1}{mc}$

$5.0 \times 10^{-4} = \frac{1}{0.400 \times c}$ (1 MARK)

$c = 5000 = 5.0 \times 10^3$ J kg^{-1} K^{-1} (1 MARK)

Depending on the line of best fit drawn, answers between 4.3×10^3 J kg^{-1} K^{-1} and 6.0×10^3 J kg^{-1} K^{-1} are acceptable.

2D The Zeroth and First Laws of Thermodynamics

Theory review questions

1 A. This is the definition of being in thermal equilibrium.

2 B. This is another definition of (and the cause of) thermal equilibrium.

3 A. This is a result of the Zeroth Law of Thermodynamics.

4 heat, work

5 B

6 A. The work that is done on the system represents a transfer of energy to the system.

7 B. In this case work is done by the system, which represents a transfer of energy out of the system.

Deconstructed exam-style question

8 a B. The heat is transferred to the gas so the gas gains the energy due to the heat transfer. Work is done by the gas (on its surroundings) which means the gas loses energy due to the work being done. 0.800 kJ = 800 J.

b D

c $\Delta U = Q + W = 300 - 800 = -500$ J (1 MARK)

$\Delta U = mc\Delta T$ $\therefore -500 = 2.0 \times 1.0 \times 10^3 \times \Delta T$ (1 MARK)

$\Delta T = -0.25$ K. The temperature decreases by 0.25 K. (1 MARK)

Exam-style questions

This lesson

9 a Heat would flow from the gas canister to the steel. (1 MARK)

b The temperature of the gas canister is greater than the temperature of the steel. (1 MARK)

10 a $\Delta U = Q + W = 300 + 0 = 300$ J (1 MARK)

b $\Delta U = Q + W = 0 - 150 = -150$ J (1 MARK)

c $\Delta U = Q + W = -180 + 420 = 240$ J (1 MARK)

11 $\Delta U = Q + W = -3300 - 2400 = -5700$ J (1 MARK)

12 Heat is transferred **away** from the system.

$\Delta U = Q + W$ $\therefore -500 = -800 + W$ (1 MARK)

$W = 300$ J (1 MARK)

Work is done **on** the balloon since the work done increases the internal energy of the balloon (shown by a positive value of work using our convention). (1 MARK)

13 Work is done **by** the system as it expands.

$\Delta U = Q + W$ $\therefore -40 = Q - 72$ (1 MARK)

$Q = 32$ J (1 MARK)

Heat is transferred **to** the gas in the syringe since it increases the internal energy of the gas. (1 MARK)

14 $\Delta U = Q + W = 100 + 1200 = 1300$ J (1 MARK)

$\Delta U = mc\Delta T$ $\therefore$ $1300 = 0.75 \times 4.2 \times 10^3 \times \Delta T$ (1 MARK)

$\Delta T = 0.41$ K $= 0.41$°C (1 MARK)

Previous lessons

15 [Air conditioners are commonly placed at high positions to distribute cool air most effectively using convection.[1]][The air from an air conditioner is cooler and denser than the rest of the air in the space so it will sink (move downwards) which displaces the warmer air, pushing it upwards towards the air conditioning system.[2]]

- I have referenced the appropriate form of heat transfer.[1]
- I have used the relevant theory: convection.[2]

This content was covered in Lesson 2B.

16 $Q_{water} = mc\Delta T = 0.120 \times 4.2 \times 10^3 \times (100 - 65) = 1.764 \times 10^4$ J (1 MARK)

$Q_{Lv} = mL_v = 0.120 \times 2.3 \times 10^6 = 2.76 \times 10^5$ J (1 MARK)

$Q_{total} = Q_{water} + Q_{Lv} = 1.764 \times 10^4 + 2.76 \times 10^5 = 2.9 \times 10^5$ J (1 MARK)

This content was covered in Lesson 2C.

Key science skills

17 [The error is a systematic error[1]][since the results are consistently less than the expected results.[2]][This is most likely due to heat being transferred away from the air.[3]]

- I have explicitly addressed the type of error.[1]
- I have used the relevant theory: the characteristics of systematic error.[2]
- I have explicitly suggested a cause for the error.[3]

Chapter 2 Review

Section A

1 A. 1000 K = (1000 − 273.15)°C

2 A. The tiles feel cold because heat is transferred quickly via conduction to the tiles since Lloyd's feet are in direct contact with the tiles. Socks do not conduct heat as well.

3 D. Being at the same temperature, being in thermal equilibrium, and having no net heat transfer are all equivalent descriptions of the relationship between two objects. If the iPhone is in thermal equilibrium with the Samsung and the Samsung is in thermal equilibrium with the Huawei then the iPhone must also be in thermal equilibrium with the Huawei (Zeroth Law).

4 B. The water continues to absorb heat but it does not increase the kinetic energy, which determines temperature.

5 C. The internal energy increases due to the heat transferred to the air. It decreases due to the work done by the air. $\therefore$ $\Delta U = 4.0 - 1.2$ J

Section B

6 [Hotter gases have greater average translational kinetic energy than the cooler air surrounding it.[1]][This means the particles in the hotter gas space themselves further apart which makes the hotter gas less dense than the cooler air and so it rises (and the cooler air sinks).[2]]

- I have used the relevant theory: temperature as a measure of average translational KE.[1]
- I have used the relevant theory: how temperature relates to density.[2]

7 a $Q = mc\Delta T$ $\therefore$ $Q = 0.120 \times 900 \times (10.0 - 25.0)$ (1 MARK)

$Q = -1.62 \times 10^3$ J

1.62×10^3 J was transferred from the goblet. (1 MARK)

b The quantity of heat transferred from the goblet is the same as the quantity transferred to the water. (1 MARK)

$Q = mc\Delta T$ $\therefore$ $1.62 \times 10^3 = m \times 4.18 \times 10^3 \times (6.9 - 5.0)$ (1 MARK)

$m = 0.204$ kg $= 204$ g (1 MARK)

8 [When the wind blows, it increases the rate of evaporation[1]][because it encourages the water molecules with the greatest kinetic energy to escape.[2]][This decreases the average translational kinetic energy, and hence temperature, of the remaining water more rapidly so that heat will be transferred from Tobias' skin to the water more rapidly.[3]]

- I have explicitly addressed the effect of the wind.[1]
- I have referenced a kinetic energy model.[2]
- I have used the relevant theory: how evaporation causes cooling.[3]

9 a $Q_{melt} = mL = 10.0 \times 2.47 \times 10^5$ J (1 MARK)

$Q_{melt} = 2.47 \times 10^6$ J

b $Q_{liquid} = Q_{total} - Q_{melt} = 3.00 \times 10^6 - 2.47 \times 10^6 = 5.3 \times 10^5$ J (1 MARK)

$Q_{liquid} = mc\Delta T$ $\therefore$ $5.3 \times 10^5 = 10.0 \times 8.20 \times 10^2 \times \Delta T$ (1 MARK)

$\Delta T = 64.6$°C $\therefore$ $T_f = T_i + \Delta T = 1538 + 64.6 = 1603$°C (1 MARK)

10 a Work is done **on** the system, which increases its internal energy.

$\Delta U = Q + W$ $\therefore$ $10 = Q + 40$ (1 MARK)

$Q = -30$ J

30 J of heat is transferred **from** the gas (2 MARKS)

b [The temperature is greater than 20°C at the end of this process[1]][because the internal energy has increased without a change of state.[2]]

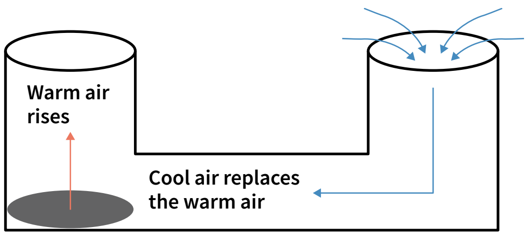
- I have explicitly addressed how the new temperature compares with the original temperature.[1]
- I have used the relevant theory: the relationship between internal energy and temperature.[2]

c The final internal energy (stage 3) is less than when the mass was resting on the plunger (stage 2)[1] because work is done by the gas as the plunger moves upwards again and there is no heat transfer due to the insulation.[2]

- I have explicitly addressed how the internal energy at stage 3 compares with internal energy at stage 2.[1]
- I have used the relevant theory: the relationship between work, heat, and internal energy.[2]

11 The matte black surface absorbs heat from the Sun via radiation and becomes hotter.[1] The black surface heats the air in the tube that is touching the surface by conduction.[2] This air is now warmer than the surrounding air which causes it to rise in the left side of the tube, which creates a convection current.[3] This convection draws in air from the right-hand side of the tube to replace the warm air.[4]

- I have explicitly addressed the role of radiation.[1]
- I have explicitly addressed the role of conduction.[2]
- I have used the relevant theory: how convection occurs.[3]
- I have explicitly addressed the role of convection.[4]



3A The electromagnetic spectrum

Theory review questions

1 D

2 visible light; microwaves; gamma waves; X-rays

3 B

4 a Radio station sends a radio wave signal

b Radio receives radio waves

c Radio emits sound

Deconstructed exam-style question

5 a C

b D

c D

d [The statement is false.[1]][Both waves travel at the same speed through a vacuum so they reach the glass at the same time.[2]] [When travelling through a medium (like glass), some of the waves are absorbed and will not reach the receiver.[3]][Due to the high frequency of gamma waves, a smaller portion of them will reach the receiver than the radio waves.[4]]

- I have explicitly addressed if the statement is true or false.[1]
- I have used the relevant theory: the speed of electromagnetic waves is the same.[2]
- I have used the relevant theory: matter absorbs of electromagnetic waves.[3]
- I have used the relevant theory: the relationship between frequency and absorption.[4]

Exam-style questions

This lesson

6 Gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, radio waves.

7 Radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays.

8 Electromagnetic waves do not need a medium to propagate.

OR

Electromagnetic waves can travel through a vacuum.

Previous lessons

9 a [Due to the hot steam having a lower density than the air,[1]] [the steam travelled via convection up to Alice's arm.[2]][The particles of the steam then collided with the particles in Alice's arm,[3]] [transferring energy via conduction.[4]]

- I have used the relevant theory: fluids rise when they have lower density.[1]
- I have explicitly addressed what the first heat transfer is.[2]
- I have used the relevant theory: particles transfer thermal energy through collisions.[3]
- I have explicitly addressed what the second heat transfer is.[4]

This content was covered in Lesson 2B.

b $Q_{water} = mc\Delta T = 1.2 \times 4.2 \times 10^3 \times 50.0 = 2.52 \times 10^5$ J (1 MARK)

$Q_{from\ kettle} = Q_{water} + Q_{surroundings}$

$2.98 \times 10^5 = 2.52 \times 10^5 + Q_{surroundings}$ (1 MARK)

$Q_{surroundings} = 4.6 \times 10^4$ J (1 MARK)

This content was covered in Lesson 2D.

Key science skills

10 $658 \text{ nm} = 658 \times 10^{-9}$ m (1 MARK)

$658 \times 10^{-9} = 6.6 \times 10^{-7}$ m (1 MARK)

3B Thermal radiation

Theory review questions

1 A. This option lists the properties of black bodies.

2 B. All objects above 0 K release thermal radiation.

3 B. Peak wavelength is inversely related to temperature, so the coolest objects will have the longest peak wavelength. Object S does not emit any radiation.

4 A. All bodies release thermal radiation from all parts of the electromagnetic spectrum.

5 B. The blue object has a greater temperature. Peak wavelength will decrease as temperature increases. As blue wavelengths are shorter than red wavelengths, objects glowing blue will be hotter.

6 A. Black bodies are good emitters as well as absorbers.

7 B. The peak wavelength is the most released wavelength.

8 across the entire spectrum; predominance of blue light in the radiation

9 D. Other types of waves are in such small amounts that they are not usually detectable on the Earth's surface.

10 B. The temperatures used in the Stephan-Boltzman law need to be measured in kelvin. It is only meaningful to describe the factor by which a temperature increases when temperatures are stated using an absolute scale (i.e. the Kelvin scale).

$T = 20 + 273.15 = 293.15$ K

$T_f = 2 \times T_i = 2 \times 293.15 = 586.3$ K

$586.3 \text{ K} = (586.3 - 273.15)°\text{C} = 313°\text{C}$

Deconstructed exam-style question

11 **a** D **b** C **c** A **d** C

e Calculate the initial temperature:

$T_i = 23.5 + 273.15 = 296.65$ K (1 MARK)

Calculate the final temperature:

$\lambda = 3560 \text{ nm} = 3.560 \times 10^{-6}$ m

$\lambda_{max} = \frac{b}{T} \therefore 3.560 \times 10^{-6} = \frac{2.898 \times 10^{-3}}{T}$

$T_f = 814.04 = 814$ K (1 MARK)

Calculate the final power:

$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{P_f}{33} = \frac{814.04^4}{296.65^4}$ (1 MARK)

$P_f = 1871.24 = 1.9 \times 10^3$ W (1 MARK)

Exam-style questions

This lesson

12 $\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{7000}$ (1 MARK)

$\lambda_{max} = 4.14 \times 10^{-7}$ m (1 MARK)

13 C (1 MARK)

$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{512}{2} = \frac{T_f^4}{T_i^4}$

$\frac{T_f}{T_i} = 4 \therefore T_f = 4 \times T_i$

The increase in power is by a factor of $4^4 = 256$. Therefore, the temperature increased by a factor of 4.

14 **a** [The reason the colour changes from "metallic silver" to red is because the majority of visible light coming from the metal changes from being reflected light to emitted light.[1]][The reason the colour changes from red to orange to white is because the proportion of light emitted at each wavelength changes.[2]][The intensity of light emitted increases as temperature increases.[3]]

- I have explicitly addressed the change in colour from "metallic silver" to red.[1]
- I have explicitly addressed the change in colour from red to orange to white.[2]
- I have explicitly addressed the relationship between temperature and intensity of radiation.[3]

b $\lambda_{max} = \frac{b}{T} \therefore 680 \times 10^{-9} = \frac{2.898 \times 10^{-3}}{T}$ (1 MARK)

$T = 4.26 \times 10^3$ K (1 MARK)

15 **a** $T = 1280 + 273.15 = 1553.15$ K (1 MARK)

$\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{1553.15} = 1.87 \times 10^{-6}$ m (1 MARK)

b [All objects emit radiation across the entire visible spectrum.[1]] [Since the peak wavelength is longer than the visible spectrum,[2]] [the intensity of visible light emitted by the glass around the longer wavelength (red) part of the visible spectrum is higher than the shorter wavelength (blue).[3]]

- I have used the relevant theory: objects emit thermal radiation across the entire spectrum.[1]
- I have referenced the peak wavelength.[2]
- I have used the relevant theory: the intensity of light near the peak wavelength is high.[3]

16 [Luna's claim is incorrect and Selene's is correct.[1]][A black body absorbs all incoming radiation and does not reflect radiation.[2]][Most of the light we see coming from the Moon is reflected light from the Sun.[3]][Hence, the bright light is not evidence of the Moon acting like a black body as Luna claims.[4]]

- I have explicitly addressed Luna's claim and Selene's claim.[1]
- I have used the relevant theory: the properties of a black body.[2]
- I have referenced the Moon's reflection of light.[3]
- I have explicitly addressed the Moon's ability to be a black body.[4]

17 **a** [Xath is emitting less power when it appears red.[1]][By Wien's Law, when the star's peak wavelength is longer, its temperature is lower[2]] [and therefore it emits less power.[3]]

- I have referenced Xath's power.[1]
- I have used the relevant theory: wavelength is inversely proportional to temperature, Wien's law.[2]
- I have used the relevant theory: temperature is proportional to power, Stefan-Botzmann law.[3]
- I have related my answer to the context of the question.

b When Xath appears white: $\lambda_{max} = \frac{b}{T}$

$405 \times 10^{-9} = \frac{2.898 \times 10^{-3}}{T_W} \therefore T_W = 7156$ K (1 MARK)

When Xath appears red: $\lambda_{max} = \frac{b}{T}$

$710 \times 10^{-9} = \frac{2.898 \times 10^{-3}}{T_R} \therefore T_R = 4082$ K (1 MARK)

c $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{P_R}{P_W} = \frac{4070^4}{7136^4}$ (1 MARK)

$\frac{P_R}{P_W} = 1.06 \times 10^{-1} \therefore 1.06 \times 10^{-1} \times 100\% = 11\%$ (1 MARK)

The power emitted when Xath is coolest is 11% of when it is hottest. (1 MARK)

18 **a** $\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{99}{P_i} = \frac{2700^4}{298^4}$ (1 MARK)

$P_i = 1.47 \times 10^{-2}$ W (1 MARK)

b $T = 35.2 + 273.15 = 308.35$ K (1 MARK)

$P = A\varepsilon\sigma T^4 \therefore 1000 = 2.00 \times \varepsilon \times 5.67 \times 10^{-8} \times 308.35^4$ (1 MARK)

$\varepsilon = 0.98$

The emissivity of a person is 0.98. (1 MARK)

c [A black body could model a person effectively.[1]][This is because a person's emissivity is very close to 1 (0.98).[2]]

- I have explicitly addressed a black body's ability to model a person.[1]
- I have used the relevant theory: the emissivity of a black body.[2]

Previous lessons

19 C (1 MARK)

This content was covered in Lesson 3A.

20 **a** $Q = mc\Delta T \ \therefore Q = 1.2 \times 6.3 \times 10^3 \times (40 - 20)$ (1 MARK)

$Q = 1.5 \times 10^5$ J (1 MARK)

b [The water will cool first[1]][as the heat capacity of water is lower than that of the unknown liquid.[2]][This means it takes less of an energy change for the same change in temperature, and so it both heats and cools faster.[3]]

- I have explicitly addressed which liquid will cool first.[1]
- I have referred to the heat capacity of both water and the unknown substance.[2]
- I have used the relevant theory: specific heat capacity.[3]

This content was covered in Lesson 2C.

Key science skills

21 [Asteri's data is more precise than Stella's data.[1]][This is because the range of Asteri's data (382 nm) is less than the range of Stella's data (534 nm).[2]]

- I have explicitly addressed whether Stella or Asteri has the more precise data.[1]
- I have used the relevant theory: the definition of precision.[2]

3C Earth's energy flow

Theory review questions

1 B. Only imbalances in heat can cause convection currents.

2 *A*-II; *B*-III; *C*-I

3 A. True, solids can convect. This occurs as a result of intense heat and pressure in Earth's mantle.

4 offshore; onshore

5 A. Onshore winds are created because the water is cooler than the land, so the breeze will also be cooler than the land.

Deconstructed exam-style question

6 **a** D

b A

c [The average temperature decreases away from the temperature due to an imbalance in radiation.[1]][The curvature of the Earth means that as you move away from the equator, the same amount of radiation is spread over a greater area.[2]][This causes less heat to be transferred from the Sun and, as a result, lower temperatures.[3]]

- I have explicitly addressed a reason for the decrease in temperature.[1]
- I have used the relevant theory: uneven distribution of radiation.[2]
- I have referenced decreased energy or heat being transferred.[3]

Exam-style questions

This lesson

7 C (1 MARK)

8 **a** At the equator, the land or ocean is warmer and in the atmosphere it is cooler. (1 MARK)

b Water at the equator is warmer and water at the southernmost part of the Pacific Ocean is cooler. (1 MARK)

c At night, the ocean is warmer and the land is cooler. (1 MARK)

9 [Thermal conduction heats the air above the land and water at the equator.[1]][The water and land at the equator generally have high temperatures due to radiation from the Sun. This is transferred to the air mainly through conduction.[2]]

- I have explicitly addressed the heat transfer occurring.[1]
- I have used the relevant theory: thermal conduction as the transfer of energy through direct contact.[2]

10 [Thermal radiation heats the land and water at the equator.[1]][Energy from the Sun in the form of electromagnetic waves is absorbed by the land and water at the equator.[2]]

- I have explicitly addressed the heat transfer occurring.[1]
- I have used the relevant theory: thermal radiation as the transfer of energy through the emission and absorption of electromagnetic waves.[2]

11 [An onshore wind is caused when radiation from the Sun warms the land faster than the ocean.[1]][Through conduction, the land warms the air above it which causes the air to rise.[2]][This creates room for the cool air from the ocean to fill its spot causing a convection cell.[3]][This rush of cool air from the ocean is an onshore wind.[4]]

- I have referenced the temperature difference between the land and ocean.[1]
- I have referenced the warmer air rising.[2]
- I used the relevant theory: convection cells in onshore winds.[3]
- I have explicitly addressed that onshore winds are from the ocean.[4]

12 [When the sea is warmer than the land in winter,[1]][conduction between the land and sea warms the land.[2]][During the summer the inverse occurs.[3]][This does not occur in inland areas which means they are hotter in summer and cooler in winter.[4]]

- I have explicitly addressed the direction of heat transfer in winter.[1]
- I have used the relevant theory: conduction.[2]
- I have explicitly addressed the direction of heat transfer in summer.[3]
- I have related my answer to the context of the question.[4]

Previous lessons

13 a $Q = mL = 0.70 \times 3.34 \times 10^5 = 2.3 \times 10^5$ J (1 MARK)

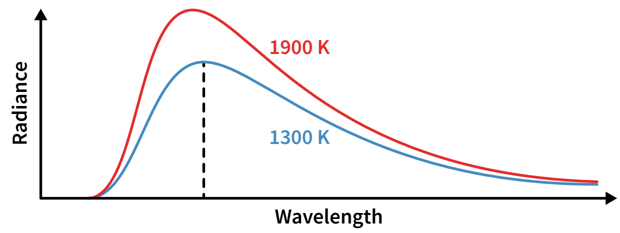
b Using the change in temperature of the 5.2 kg of water:

$Q = mc\Delta T = 5.2 \times 4.2 \times 10^3 \times (23.0 - 10.8)$ (1 MARK)

$Q = 2.7 \times 10^5$ J (1 MARK)

This content was covered in Lesson 2C.

14 a



- I have drawn a curve with greater radiance than the 1300 K curve.
- I have drawn a curve with a peak to the left of the 1300 K peak.
- I have drawn a curve with an appropriate shape.

b $\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{1300}$ (1 MARK)

$\lambda_{max} = 2.23 \times 10^{-6}$ m (1 MARK)

c $\varepsilon = 1.00$ as it is a black body. (1 MARK)

$P = A\varepsilon\sigma\left(T_f^4 - T_i^4\right) = 1.39 \times 1.00 \times 5.67 \times 10^{-8} \times (1900^4 - 1300^4)$ (1 MARK)

$P = 8.02 \times 10^5$ W (1 MARK)

This content was covered in Lesson 3B.

Key science skills

15 a Independent: location (1 MARK)
Dependent: amount of water collected (1 MARK)
Controlled: rain gauge size **OR** time left out (1 MARK)

b [They could have left the rain gauges out for a longer period of time (or repeated it multiple times).[1]][This would allow more data to be gathered and would increase reliability and validity of data.[2]][They could also use more rain gauges in different areas.[3]][This would increase the reliability by reducing the effect of random error.[4]]

- I have explicitly addressed one improvement to the experiment.[1]
- I have referenced the reliability of the experiment.[2]
- I have explicitly addressed another improvement to the experiment.[3]
- I have referenced the reliability of the experiment.[4]

3D The greenhouse effect

Theory review questions

1 P best represents the Earth as it has a lower surface temperature. We know it will have a peak in the infrared spectrum away from visible light.

Q best represents the Sun. Its peak will be in the visible spectrum.

2 reflected; absorbed; transmitted

3 D. The same wavelength may be absorbed by one material and not the other. Similarly, one wavelength may pass through a material and another may be absorbed by the same material. Both are factors.

4 B. The emitted wavelength is always dependent on the temperature of the object that emits it.

5 A. Reflection is the same wave changing direction when it interacts, so it has to have the same wavelength.

6 Q

This is because they represent reflected sunlight, so they will have a similar spectrum as the Sun.

7 emitted; P

The temperature of the atmosphere is going to be much cooler than that of the Sun, so it will emit radiation similar to that displayed in graph P.

8 longer (infrared); shorter

9 A

Deconstructed exam-style question

10 a C **b** B **c** D

d [The Earth's temperature is a balance of this incoming and outgoing radiation with other factors such as reflection and absorption by the atmosphere.[1]][Incoming radiation from the Sun is of a shorter wavelength[2]][and radiation from the Earth is made of longer infrared radiation.[3]]

- I have explicitly addressed Earth's temperature as a balance of incoming and outgoing radiation.[1]
- I have used the relevant theory: the Sun's radiation.[2]
- I have used the relevant theory: the Earth's radiation.[3]

Exam-style questions

This lesson

11 B (1 MARK)

12 **a** [Infrared radiation.[1]][The infrared in Earth's radiation is generally a longer wavelength than the infrared emitted from the Sun.[2]]

- I have explicitly addressed the shared part of the electromagnetic spectrum.[1]
- I have explicitly addressed the difference in the two spectrums.[2]

b Carbon dioxide, methane, water vapour (other greenhouse gases are acceptable) (2 MARKS)

13 **a** [The remaining 95% is absorbed by greenhouse gases in the atmosphere.[1]][This is then re-emitted back to Earth.[2]]

- I have referenced absorption by greenhouse gases.[1]
- I have used the relevant theory: the greenhouse effect.[2]

b The infrared spectrum (1 MARK)

14 [The energy Earth radiates is in the infrared zone[1]][which, as seen in the graph,[2]][coincides with a wavelength of high absorption for CO_2.[3]] [Incoming radiation is in the visible spectrum for which CO_2 is a poor absorber.[4]]

- I have referred to the spectrum that Earth radiates.[1]
- I have explicitly addressed information from the graph.[2]
- I have used the relevant theory: the absorption spectrum of greenhouse gases.[3]
- I have referred to the relationship between the Sun's emission spectrum and CO_2's absorption spectrum.[4]

15 [The spectrum emitted from the Earth is made up almost entirely by the infrared spectrum due to Earth's low temperature.[1]][As the Sun is much hotter, it releases shorter wavelength light from the infrared, visible, and ultraviolet parts of the spectrum.[2]]

- I have explicitly addressed the emission spectrum of the Earth.[1]
- I have explicitly addressed the emission spectrum of the Sun.[2]

16 [Venus' temperature would be higher than Earth's.[1]][This is due to the much higher percentage of carbon dioxide in the atmosphere (96.5%) and Venus' proximity to the Sun which means it receives more solar radiation.[2]][The higher percentage of greenhouse gases causes an increase in the amount of energy absorbed due to the greenhouse effect thereby increasing the planet's temperature.[3]]

- I have explicitly addressed that Venus' temperature would be greater than Earth's.[1]
- I have referenced the information provided.[2]
- I have used the relevant theory: the greenhouse effect.[3]

Previous lessons

17 $\Delta U = Q + W = -17 + 9.0$ (1 MARK)

$\Delta U = -8$ kJ (1 MARK)

This content was covered in Lesson 2D.

18 **a** $\lambda_{max} = 9760 \text{ nm} = 9760 \times 10^{-9} = 9.760 \times 10^{-6} \text{ m}$

$\lambda_{max} = \frac{b}{T} \therefore 9.760 \times 10^{-6} = \frac{2.898 \times 10^{-3}}{T}$ (1 MARK)

$T = 296.9$ K (1 MARK)

$T = 23.8°\text{C}$ (1 MARK)

b $P \propto T^4$

$T_f = 2 \times T_i$

$2^4 = 16$ (1 MARK)

$P_f = P_i \times 16 = 5356 \times 16$

$P_f = 85\,696$ W (1 MARK)

$\Delta P = P_f - P_i = 85\,696 - 5356 = 8.034 \times 10^4$ W (1 MARK)

This content was covered in Lesson 3B.

Key science skills

19 [Bronte's claim is correct, and Endrico's is incorrect.[1]][Theories are explanations of physical phenomena that have been repeatedly confirmed by experimental evidence.[2]][Hypotheses are proposed explanations of relationships that are yet to be tested.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: definition of a theory.[2]
- I have used the relevant theory: definition of a hypothesis.[3]

3E Modelling effects on the climate

Theory review questions

1 B. A change in Earth's (or a region's) temperature is only considered climate change if it lasts for more than 30 years.

2 **a** A **b** B **c** B

Same explanation as Question 1.

3 D. Albedo is the fraction of solar radiation reflected by a surface (not absorbed and re-emitted).

4 IV. Negative feedback is demonstrated because the initial change in Earth's temperature is counteracted by the effect of the change. All the other options are positive feedback.

5 A. We would observe positive feedback in the ball and hill scenario, since the initial change in speed decreases the ball's height, which further increases the speed of the ball. In the other scenario the initial change in speed is resisted because of the upward slope.

6 A. This is why we attribute rising temperatures to CO_2 even though it is not actually the main contributor to the regular greenhouse effect. Because it is being emitted at a rate faster than it leaves the atmosphere, it is driving the **change** in the amount of energy trapped, causing temperatures to rise.

7 B. The horizontal and vertical axes have been cut to make it look like there is a significant downward trend, but in option A we can see that this is not a significant fluctuation for the data.

8 A. The non-linear logarithmic vertical axis hides the size and the significance of a spike in the plot, which is much more obvious in option B.

9 A. Good scientific method can still result in high uncertainty (although it should aim to minimise it).

10 A. Climate is the long-term average of the weather. Predicting the weather on a specific day requires much more precision, since the weather from one day to the next varies extremely compared to the climate.

Deconstructed exam-style question

11 **a** A

b A. If an increase in temperature causes CO_2 levels to increase, from **a** we expect that this increase in CO_2 levels will increase temperatures. This is a positive feedback, as the change will be magnified.

c C

d [It is justified to say that, historically, changes in CO_2 were not responsible for many initial increases in temperature. However, we know that extra CO_2 traps more heat and raises temperatures further.[1]][Additionally, the graph shows a strong correlation between CO_2 and temperature, with the most significant warming occurring while CO_2 levels were rising,[2]][which is consistent with positive feedback.[3]][These factors indicate that CO_2 levels could affect temperature and so Bec's claim is unjustified.[4]]

- I have used the relevant theory: CO_2's effect on the climate.[1]
- I have referenced how the graph shows that most warming occurs while/just after CO_2 levels rise.[2]
- I have explicitly addressed positive feedback.[3]
- I explicitly addressed why Bec's claim is unjustified.[4]

Exam-style questions

This lesson

12 B (1 MARK)

Lower temperatures should result in more snowfall, which would be positive feedback.

13 A (1 MARK)

14 A (1 MARK)

15 C (1 MARK)

The enhanced greenhouse effect is by definition due entirely to humans.

16 A (1 MARK)

As covered in Lesson 3D, nearly all of the energy coming into the Earth is balanced by the energy leaving it. The enhanced greenhouse effect's dramatic impact on temperature is due to it causing an imbalance between the amount of energy flowing into the Earth and out.

17 B (1 MARK)

18 [Since carbon dioxide has a longer lifetime in the atmosphere,[1]][it is able to build up more than methane, increasing the temperature of the atmosphere by a greater amount.[2]]

- I have used the relevant theory: lifetimes of methane and carbon dioxide.[1]
- I have used the relevant theory: effect of lifetime on atmospheric concentration.[2]

Previous lessons

19 If two systems are both in thermal equilibrium with a third system, they are also in thermal equilibrium with each other. (1 MARK)

This content was covered in Lesson 2D.

20 [Due to the increased temperature of the ocean on the western coast of South America during El Niño, we would expect offshore winds to occur more and onshore winds less.[1]][This is because the air above the ocean will be warmer than the air above the land,[2]][resulting in a pressure difference that causes the air to travel via convection towards the ocean.[3]]

- I have explicitly addressed how offshore and onshore winds are affected.[1]
- I have explicitly addressed the difference in temperature between the air above the ocean and the air above the land.[2]
- I have used the relevant theory: mechanics of onshore and offshore winds.[3]
- I have related my answer to the context of the question.

This content was covered in Lesson 3C.

Key science skills

21 [Climate scientists build reliability when collecting data by running experiments multiple times to ensure repeatability.[1]][Other climate scientists will attempt similar experiments in order to determine whether the results of the original experiments are reproducible and should be taken seriously.[2]]

- I have used the relevant theory: repeatability in climate data collection.[1]
- I have used the relevant theory: reproducibility in climate data collection.[2]

3F Thermodynamic principles in housing and transportation

Theory review questions

1 D. Around 40% for heating and cooling the house/people, 20% for heating water, and 10% for cooking and refrigeration.

2 B. In the northern hemisphere the Sun traces an arc across the southern sky (opposite to the southern hemisphere).

3 E. Good passive designs maximise heat gain and minimise heat loss in winter and they minimise heat gain and maximise heat loss during summer.

4 I; III; IV. Insulation, double glazed windows, and sealing all help to prevent heat transfer (in either direction). Eaves mainly reduce heat gain from the Sun in summer (but do not reduce heat loss) and solar chimneys mainly encourage heat loss by natural convection.

5 D

6 C. Thermal mass reduces the temperature during the day (regardless of the season) by absorbing heat and it increases the temperature during the night by releasing heat (which can be removed with other passive designs during summer).

7 A. Heat pumps move thermal energy but do not rely on creating more thermal energy.

8 B. Evaporation occurs at a much slower rate when the air is already holding a lot of water (i.e. it is humid) but it is effective in dry air (low humidity).

9 C. The main purpose of an automobile is to travel, so we should compare the pollution based on equal distances travelled.

10 C. Same explanation as Question 9.

Deconstructed exam-style question

11 a B. Warm air rises because it is less dense.

b C. Rising warm air will draw cooler air to replace it. This is natural convection. It can cool a house if it is designed so that air can be drawn from a cooler region outside (such as air from near a body of water).

c [The Sun's energy can be used to create convective air movement[1]] [by using a surface that absorbs sunlight well to heat up the air near it (like in a solar chimney)[2]] [which will then rise and draw air from a cooler region into the house.[3]]

- I have explicitly addressed how the Sun's energy can be used for cooling.[1]
- I have used the relevant theory: capturing energy in using absorption to heat air.[2]
- I have used the relevant theory: drawing cool air into the house.[3]

Exam-style questions

This lesson

12 [No, insulation should be used in hot environments too[1]] [because it prevents heat transfer in both directions which means it helps prevent heat gain in hot environments.[2]]

- I have explicitly addressed whether insulation should be used in hot environments.[1]
- I have used the relevant theory: insulation prevents heat flow in both directions.[2]

13 Conduction (1 MARK)

14 [Burning gas is a more efficient way of creating thermal energy than using electricity. This is because burning gas converts the chemical energy directly into thermal energy whereas electricity acts as a middle step between some other energy form (usually chemical energy from coal in Victoria) and thermal energy.[1]] [Burning gas also releases less carbon dioxide per unit of energy released than the coal that most of Victoria's electricity is derived from.[2]]

- I have explicitly addressed one reason that gas is preferred to electricity.[1]
- I have explicitly addressed a second reason that gas is preferred to electricity.[2]

15 [The electricity that electric cars use is often produced from fossil fuels such as coal, which do create greenhouse gas emissions.[1]] [Electric cars are still helpful because the process of converting chemical energy from coal at a power plant into the motion of the car is generally more efficient than converting chemical energy from petrol into motion of the car in a combustion engine.[2]] [As electricity generation technologies become cleaner in the future due to increasing use of renewable energy sources, electric cars will become cleaner to drive too.[3]]

- I have explicitly addressed the reason that the statement is not necessarily true.[1]
- I have explicitly addressed why electric cars are still helpful now.[2]
- I have explicitly addressed why electric cars will become cleaner in the future.[3]

Previous lessons

16 Infrared (1 MARK)

This content was covered in Lesson 3B.

17 [Greenhouse gases absorb longer wavelength infrared radiation well but not shorter wavelength infrared, visible, and ultraviolet radiation.[1]] [The vast majority of the energy radiated from Earth towards space is longer wavelength infrared radiation whereas a large portion of energy radiated towards Earth from the Sun is shorter wavelength infrared, visible, and ultraviolet radiation.[2]]

- I have used the relevant theory: greenhouse gas absorption of different types of radiation.[1]
- I have used the relevant theory: different types of radiation travelling in different directions.[2]

This content was covered in Lesson 3D.

Key science skills

18 [The investigation is not valid[1]] [because there are controlled variables that are not sufficiently maintained, which means the window type (independent variable) is not the only significant variable that affects heat loss in this case.[2]] [For this investigation to be valid, the student should measure the heat loss at similar times of day when the temperature is the same and ideally from the same or similar houses.[3]]

- I have explicitly addressed the validity of the investigation.[1]
- I have used the relevant theory: experimental validity and variables.[2]
- I have related my answer to the context of the question.[3]

Chapter 3 Review

Section A

1 B. Onshore winds occur when the ocean is cooler than the land.

2 D. LPG is a fossil fuel, not a greenhouse gas.

3 C. The tree blocks light (radiation) in the summer, keeping the home cool.

4 B. The greenhouse effect existed before human civilisation and continues today but is enhanced due to the actions of humanity.

5 A

$\lambda_{max} = \frac{b}{T} \therefore 230 \times 10^{-9} = \frac{2.898 \times 10^{-3}}{T}$

$T = 12\,600$ K

Section B

6 Two of the following: all travel at the speed of light in a vacuum; can travel through a vacuum (no medium required); have an associated wavelength, frequency and energy; transfer energy; are transverse waves; or other properties not covered in Chapter 3

7 [Although the mantle is solid, convection cells form within it over geological periods of time due to the immense temperature and pressure.[1]][Hot parts of the mantle are less dense than cooler parts and rise towards the Earth's crust.[2]][At the crust they cool and then are pulled down towards the core to reheat.[3]]

- I have explicitly addressed the conditions of convection in the Earth's mantle.[1]
- I have referenced the hot parts of the mantle rising towards the crust.[2]
- I have referenced the cool parts of the mantle sinking towards the core.[3]

8 a [The studio light is likely to be at higher temperature.[1]][This is as temperature is inversely proportional to peak wavelength.[2]] [Since white light is a combination of the entire visible spectrum and is made up of larger proportions of shorter wavelength radiation than yellow light, the source of the white light is hotter.[3]]

- I have explicitly addressed which light will be at a higher temperature.[1]
- I have referenced Wien's law.[2]
- I have used the relevant theory: electromagnetic spectrums of real bodies.[3]

b $T = 20.0 + 273.15 = 293.15$ K (1 MARK)

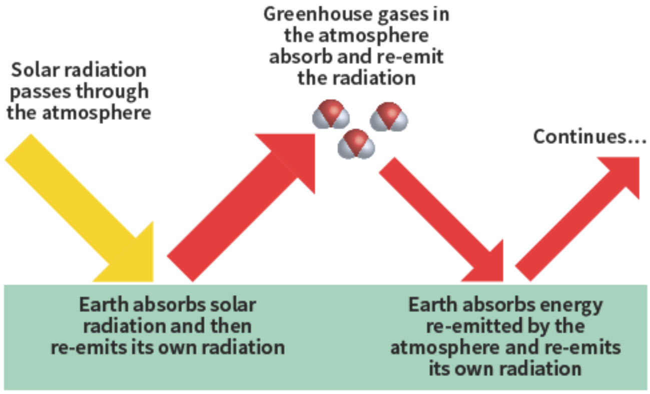
$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{30}{P_i} = \frac{3500^4}{293.15^4}$ (1 MARK)

$P_i = 1.48 \times 10^{-3}$ W (1 MARK)

c $\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{3500}$ (1 MARK)

$\lambda_{max} = 828$ nm (1 MARK)

9 [Greenhouse gases absorb and re-emit much of Earth's radiation whilst letting more solar radiation transmit through them.[1]][By re-emitting radiation back to the Earth, greenhouse gases serve to prevent energy from escaping the Earth, thereby increasing its temperature through the greenhouse effect.[2]]



- I have explicitly addressed greenhouse gases and their relationship to the Earth's and solar radiation.[1]
- I have used the relevant theory: greenhouse gases.[2]
- I have drawn greenhouse gases in the atmosphere absorbing and re-emitting radiation emitted by the Earth.
- I have graphically differentiated between radiation from the sun and radiation re-emitted from the Earth.

10 a Diesel vehicle (1 MARK)

b Electric vehicle (1 MARK)

c [Currently, most of the CO_2 that electric vehicles 'release' is as a result of burning fossil fuel to charge the car's batteries.[1]][If the electricity used to power the car is produced from renewable energy instead, there is no longer an associated CO_2 release when it is driven.[2]] [Therefore, the electric vehicle would become the best choice based on CO_2 released per kilometre.[3]]

- I have used the relevant theory: burning fossil fuels to produce energy.[1]
- I have explicitly addressed electric vehicles when powered by renewable energy.[2]
- I have explicitly addressed which vehicle would be the best choice.[3]

11 [Positive feedback occurs when the results of an initial change magnify that change.[1]][An example of this is the melting of sea ice.[2]][If the global average temperature increases, we would expect more sea ice to melt. As the ocean has a lower albedo than the ice it replaces, it absorbs more radiation which makes the Earth warmer. This causes more ice to melt, completing the positive feedback loop.[3]]

- I have explicitly addressed the definition of positive feedback.[1]
- I have explicitly addressed an example from the real world.[2]
- I have used the relevant theory: positive feedback.[3]

Unit 1, AOS 1 Review

Section A

1 A. With darker soil the Moon would absorb more visible light. Since visible light is a major part of the Sun's spectrum, we expect the Moon's albedo to be decreased, increasing the energy absorbed.

This content was covered in Lesson 3E.

2 B. $\Delta U = Q + W = (Q_{in} - Q_{out}) + (W_{on} - W_{by})$

$10 = (5 - 0) + (0 - W_{by}) \ \therefore W_{by} = -5 \text{ kJ}$

This content was covered in Lesson 2D.

3 C. The Sun emits infrared the most, followed by visible and then ultraviolet light. X-rays make up the smallest amount of the Sun's emissions.

This content was covered in Lesson 3B.

4 B

This content was covered in Lesson 2B.

5 A. $\frac{Q}{t}$ is the rate heat is being transferred via conduction. Since ΔT changes by a factor of $\frac{\Delta T_f}{\Delta T_i} = \frac{-12-(-18)}{-6-(-18)} = \frac{1}{2}$ and $\frac{Q}{t} \propto \Delta T$, $\frac{Q}{t}$ also changes by a factor of $\frac{1}{2}$. So $\frac{Q_f}{t_f} = \frac{\Delta T_f}{\Delta T_i} \times \frac{Q_i}{t_i} = \frac{1}{2} \times 2 = 1 \text{ J s}^{-1}$.

This content was covered in Lesson 2B.

Section B

6 [Thermal radiation will be affected by the reflectivity of the liquid,[1]] [conduction will be affected by the thermal insulation,[2]] [and convection will be affected by the viscosity.[3]]

- I have explicitly addressed which property affects thermal radiation.[1]
- I have explicitly addressed which property affects conduction.[2]
- I have explicitly addressed which property affects convection.[3]

This content was covered in Lessons 2B and 3B.

7 Room filled with air

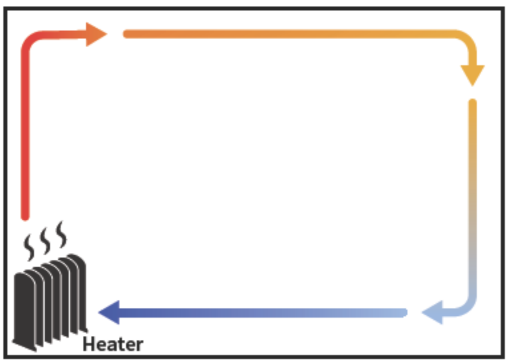


Image: A-spring/Shutterstock.com

- I have drawn arrows representing hot air rising from the radiator to the top of the room.
- I have drawn arrows that loop around the boundaries of the room, representing the warm air cooling and falling back to the ground.
- I have drawn arrows that return to the heater, representing the cool air replacing the air rising from the heater.

This content was covered in Lesson 2B.

8 a Decrease (1 MARK)

This content was covered in Lesson 2B.

b [The change in potential and kinetic energy will not be equal[1]] [because system *A* stores more of its internal energy as potential energy than as kinetic energy.[2]]

- I have explicitly addressed whether the change in potential energy and kinetic energy will be equal.[1]
- I have referenced that the internal energy of system *A* is not spread equally between potential and kinetic energy.[2]

This content was covered in Lesson 2A.

9 a Absorption (1 MARK)

This content was covered in Lesson 2B.

b [The interaction is the Earth warming the atmosphere via conduction.[1]] [This happens most significantly near the equator, since these regions absorb the most radiation from the Sun.[2]]

- I have used the relevant theory: conduction in the atmosphere.[1]
- I have explicitly addressed the areas of the Earth where indirect warming of the atmosphere is most significant.[2]

This content was covered in Lesson 3C.

c Ocean currents **OR** onshore/offshore winds (1 MARK)

This content was covered in Lesson 3C.

10 a Use any two points on the line for honey to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{76 - 20}{(40 - 0) \times 10^3}$

$gradient = 1.4 \times 10^{-3} \text{ K J}^{-1}$ (1 MARK)

$gradient = \frac{rise}{run} = \frac{\Delta T}{Q}$

The equation relating Q and ΔT is $Q = mc\Delta T \ \therefore gradient = \frac{1}{mc}$

$1.4 \times 10^{-3} = \frac{1}{0.300 \times c}$ (1 MARK)

$c = 2.38 \times 10^3 = 2.4 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$ (1 MARK)

OR

Use any two points on the line for honey to get Q and ΔT.

$Q = (40 - 0) \times 10^3 = 40 \times 10^3$ and $\Delta T = 76 - 20 = 56 \text{ K}$ (1 MARK)

$Q = mc\Delta T \therefore 40 \times 10^3 = 0.300 \times c \times 56$ (1 MARK)

$c = 2.38 \times 10^3 = 2.4 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$ (1 MARK)

This content was covered in Lesson 2C.

b Use any two points on the line for **honey** to get Q and ΔT for the **new water** sample.

$Q = mc\Delta T \therefore (40 - 0) \times 10^3 = m \times 4200 \times (76 - 20)$ (1 MARK)

$m = 0.17 \text{ kg}$ (1 MARK)

This content was covered in Lesson 2C.

11 a Active cooling (1 MARK)

This content was covered in Lesson 3F.

b [The higher-energy particles on the surface of water are able to escape in a gaseous state (evaporate),[1]][reducing the average translational kinetic energy of the remaining water particles. This reduces the temperature of the system.[2]]

- I have used the relevant theory: how evaporation occurs.[1]
- I have used the relevant theory: how evaporation cools.[2]

This content was covered in Lesson 2C.

12 a [Temperature measures the average translational kinetic energy in a system from particles' random disordered motion.[1]][Absolute zero represents the temperature where a system's particles have the lowest possible amount of this kinetic energy.[2]]

- I have used the relevant theory: temperature as a measure of average translational kinetic energy of particles.[1]
- I have explicitly addressed the physical meaning of absolute zero.[2]

This content was covered in Lesson 2A.

b $470.4 \text{ K} = (470.4 - 273.15)°\text{C} = 197.3°\text{C}$ (1 MARK)

This content was covered in Lesson 2A.

c $Q = mL = 0.150 \times 800 \times 10^3 = 1.20 \times 10^5 \text{ J}$ (1 MARK)

This content was covered in Lesson 2C.

d $\frac{Q}{t} \propto \Delta T$

ΔT changes by a factor of $\frac{45.0}{180} = \frac{1}{4}$, so $\frac{Q}{t}$ does too.

$\frac{Q}{t} = \frac{1}{4} \times \frac{-2.00 \times 10^3}{1} \therefore \frac{Q_f}{t_f} = \frac{Q_f}{1} = \frac{1}{4} \times \frac{-2.00 \times 10^3}{1} \therefore Q_f = -500 \text{ J}$ (1 MARK)

$W = W_{on} - W_{by} = 150 - 400 = -250 \text{ J}$ (1 MARK)

$U = Q + W = -750 \text{ J}$ (1 MARK)

This content was covered in Lessons 2B and 2D.

e [Increase.[1]][With the seal gone, air would be able to flow into and out of the flask, removing thermal energy through convection.[2]]

- I have explicitly addressed how the rate that thermal energy leaves the antifreeze would change.[1]
- I have explicitly addressed why the rate would change.[2]

This content was covered in Lesson 2B.

13 [A significant portion of the solar radiation that reaches Earth's surface is in the visible spectrum.[1]][Since white light is made up of the entire spectrum of visible light,[2]][and albedo is the fraction of solar radiation reflected by a surface,[3]][surfaces that are good at reflecting white light have a high albedo.[4]]

- I have explicitly addressed that a high amount of solar radiation is in the visible spectrum.[1]
- I have explicitly addressed that white light is made up of visible light.[2]
- I have used the relevant theory: what albedo measures.[3]
- I have related my answer to the context of the question.[4]

This content was covered in Lessons 3A, 3D, and 3E.

14 a [The enhanced greenhouse effect has increased the amount of thermal energy retained by the Earth.[1]][Humans have induced the effect (primarily) by raising atmospheric CO_2 levels through our CO_2 emissions.[2]][This results in a positive feedback loop that causes more greenhouse gases to enter the atmosphere, strengthening the effect.[3]]

- I have explicitly addressed the way that the amount of thermal energy retained by the Earth has been altered by the enhanced greenhouse effect.[1]
- I have explicitly addressed how human activity has resulted in the enhanced greenhouse effect.[2]
- I have used the relevant theory: the feedback loop between greenhouse gases and temperature.[3]

This content was covered in Lesson 3E.

b Constructing cities with an albedo lower than their environment increases the amount of thermal energy retained by the Earth. (1 MARK)

This content was covered in Lesson 3E.

c Uncertainty (1 MARK)

Uncertainty is quantitative, while reliability is qualitative. '90% confidence' indicates the use of a confidence interval, which is a measure of uncertainty.

This content was covered in Lessons 1C and 3E.

d P_1 indicates the power for a temperature of 40.3°C, and P_2 for 41.9°C.

$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4} \therefore \frac{P_2}{4.21 \times 10^{15}} = \frac{(41.9 + 273.15)^4}{(40.3 + 273.15)^4}$ (1 MARK)

$P_2 = 4.297 \times 10^{15} \text{ W}$ (1 MARK)

$\Delta P = P_2 - P_1 = (4.297 - 4.21) \times 10^{15} = 9 \times 10^{13} \text{ W}$ (1 MARK)

This content was covered in Lesson 3B.

REVIEW

e $\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{41.9 + 273.15}$ (1 MARK)

$\lambda_{max} = 9.20 \times 10^{-6}$ m (1 MARK)

This content was covered in Lesson 3B.

f [Even though an increase in the rate of CO_2 emissions is correlated with an increase in temperature, that does not mean one is causing the other.[1]][Additionally, CO_2 builds up over a very long time, so even if the rate that CO_2 is emitted stopped increasing, the level of atmospheric CO_2 would continue to increase which would likely cause temperatures to continue to rise due to the greenhouse effect.[2]] [Since both parts of Josh's conclusion are not supported by the graphs, his conclusion is incorrect.[3]]

- I have used the relevant theory: correlation does not imply causation.[1]
- I have used the relevant theory: lifetime and/or buildup of CO_2.[2]
- I have explicitly addressed why Josh's claim is incorrect.[3]

This content was covered in Lesson 3E.

4A What is electricity?

Theory review questions

1. B. Charge is a property of subatomic particles, so in order for charge to move, the particles must move themselves.
2. II; III. I is an open circuit and IV provides no path for charges to reduce electric potential energy.
3. charge carriers; electrical source; potential energy; potential difference; current
4. **a** B. The vans receive an equal amount of bread.

   b A. Charge carriers with equal charge magnitude receive an equal amount of electric potential energy.
5. C. The energy delivered by the battery over a period of time is not equal to the total energy stored inside the battery. Power is a rate of change of energy, not an amount of energy.
6. A. Power and current depend on the circuit that an ideal source is connected to.

Deconstructed exam-style question

7 **a** A

b C

c $V = \frac{E}{Q}$ $\therefore 40 \times 10^3 = \frac{400 \times 10^3}{Q}$ (1 MARK)

$Q = 10$ C (1 MARK)

$n_e = \frac{-Q}{-e} = \frac{-10}{-1.6 \times 10^{-19}}$ (1 MARK)

$n_e = 6.3 \times 10^{19}$ (1 MARK)

Exam-style questions

This lesson

8 **a** $P = VI$ $\therefore 220 = 20 \times I$

$I = 11$ A (1 MARK)

b $P = \frac{E}{t}$ $\therefore 220 = \frac{E}{12}$

$E = 2640 = 2.6 \times 10^3$ J (1 MARK)

c $I = \frac{Q}{t}$ $\therefore 11 = \frac{Q}{12}$

$Q = 132$ C (1 MARK)

$n_e = \frac{-Q}{-e} = \frac{-132}{-1.6 \times 10^{-19}} = 8.3 \times 10^{20}$ electrons (1 MARK)

9 $V = \frac{E}{Q}$ $\therefore 5.0 = \frac{E}{3.0}$

$E = 15$ J (1 MARK)

10 **a** $P_1 = \frac{E}{t_1}$ $\therefore 10 = \frac{E}{8.0}$

$E = 80$ J (1 MARK)

$P_2 = \frac{E}{t_2}$ $\therefore 20 = \frac{80}{t_2}$

$t_2 = 4.0$ s (1 MARK)

OR

The replacement component uses energy twice as fast as the first component (20 W = 2 × 10 W) so the same amount of energy would be used in half the time. (1 MARK)

$t_2 = \frac{t_1}{2} = \frac{8.0}{2} = 4.0$ s (1 MARK)

b [Since the same source was used, the voltage across each component was equal.[1]][This is because ideal sources provide a constant potential difference.[2]][Since $P = VI$, the second component drew twice as much current as the first.[3]]

- I have explicitly addressed the voltage of each component.[1]
- I have used the relevant theory: ideal voltage sources provide constant potential difference.[2]
- I have explicitly addressed the current of each component.[3]

11 1 hour = 60 × 60 = 3600 s

$P = \frac{E}{t} = \frac{3.6 \times 10^3}{3600} = 1.0$ W (1 MARK)

$P = VI$ $\therefore 1.0 = V \times 2.0$ (1 MARK)

$V = 0.50$ V (1 MARK)

OR

1 hour = 60 × 60 = 3600 s

$I = \frac{Q}{t}$ $\therefore 2.0 = \frac{Q}{3600}$

$Q = 7.2 \times 10^3$ C (1 MARK)

$V = \frac{E}{Q} = \frac{3.6 \times 10^3}{7.2 \times 10^3}$ (1 MARK)

$V = 0.50$ V (1 MARK)

12 $V = \frac{E}{Q}$ $\therefore 66 \times 10^3 = \frac{500 \times 10^6}{Q}$ (1 MARK)

$Q = 7.6 \times 10^3$ C (1 MARK)

OR

$P = \frac{E}{t} = \frac{500 \times 10^6}{0.50} = 1.0 \times 10^9$ W

$P = VI$ $\therefore 1.0 \times 10^9 = 66 \times 10^3 \times I$

$I = 15.2 \times 10^3$ A (1 MARK)

$I = \frac{Q}{t}$ $\therefore 15.2 \times 10^3 = \frac{Q}{0.50}$

$Q = 7.6 \times 10^3$ C (1 MARK)

13 [Kendall is correct.[1]][Electric charge is a property of subatomic particles and cannot be transferred between subatomic particles.[2]][Therefore, because current is a flow of charge, there must be physical movement of charged particles for there to be a current.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: electric charge is a property of subatomic particles.[2]
- I have used the relevant theory: electric current as the movement of charged particles.[3]

14 [The cell transforms stored chemical energy into the electric potential energy it transfers to the circuit.[1]][The electric potential energy is transferred through the wires by the movement of charge carriers.[2]] [The light bulb then transforms the electric potential energy of the charge carriers in the circuit into light and thermal energy.[3]]

- I have explicitly addressed the storage and transformation of energy in the battery.[1]
- I have used the relevant theory: flow of energy in a circuit.[2]
- I have explicitly addressed the transformation of energy at the light bulb.[3]

Previous lessons

15 **a** Radiation (1 MARK)

b Red (1 MARK)

This content was covered in Lessons 2B and 3B.

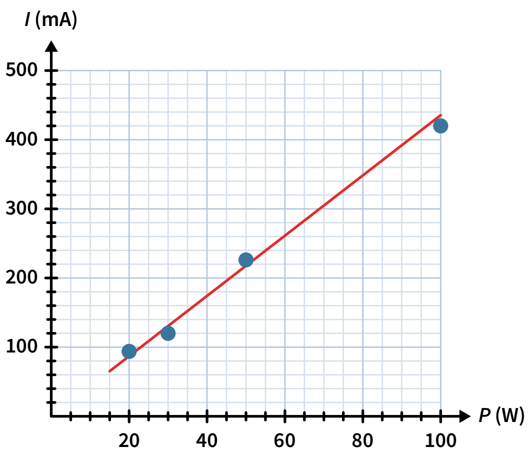
16 [The trend shown in the highlighted area is climatic,[1]][since it occurs over a large (>30 year) timeframe.[2]]

- I have explicitly addressed whether the trend is climatic.[1]
- I have used the relevant theory: climatic trends occur over periods greater than 30 years.[2]

This content was covered in Lesson 3E.

Key science skills

17 **a**



- I have plotted power on the horizontal axis and current on the vertical axis.
- I have included axis labels and appropriate units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each data point.
- I have included a line of best fit.

b $P = VI$

$gradient = \frac{rise}{run} = \frac{I}{P} = \frac{1}{V}$

Using two points on the line of best fit:

$gradient = \frac{rise}{run} = \frac{(400 - 100) \times 10^{-3}}{92.5 - 23} = 0.0043$ (1 MARK)

$V = \frac{1}{0.0043} = 232\ \text{V}$

The camera network is operating at 232 V. (1 MARK)

Note that a range of answers is acceptable based on the points chosen from the line of best fit.

4B Resistance and Ohm's law

Theory review questions

1 B. Temperature affects material resistivity. Geometry (length, shape) does not affect resistivity.

2 Y. Applying $R = \rho\frac{L}{A}$ to objects of equal length, the smallest resistivity and the largest cross-sectional area gives the lowest resistance.

3 W. Applying $R = \rho\frac{L}{A}$ to objects of equal length, the largest resistivity and the smallest cross-sectional area gives the highest resistance.

4 B, C. Ohmic devices have constant gradients passing through the origin.

5

Property	Affects resistivity?	Affects resistance?
Length		✓
Cross-sectional area		✓
Material	✓	✓
Temperature	✓	✓

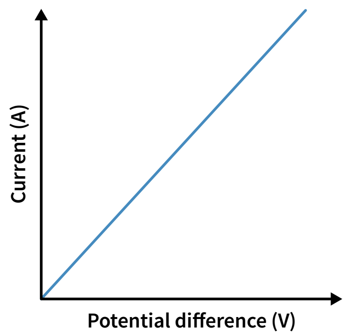
6 B. A resistor does not store or provide energy.

Deconstructed exam-style question

7 **a** C

b B. An *I-V* graph for an ohmic device is linear (constant gradient) since its resistance is constant, and it is positive since an increase in potential difference causes an increase in current.

c



- I have drawn a line with a positive and linear gradient passing through the origin.
- I have included axis labels and appropriate units.

Exam-style questions

This lesson

8 $A = \pi r^2 = \pi \times (2.0 \times 10^{-3})^2 = 1.26 \times 10^{-5}\ \text{m}^2$ (1 MARK)

$R = \rho\frac{L}{A} = 1.7 \times 10^{-8} \times \frac{0.30}{1.26 \times 10^{-5}} = 4.1 \times 10^{-4}\ \Omega$ (1 MARK)

9 $V = IR \ \therefore 12 = 0.20 \times R$

$R = 60\ \Omega$ (1 MARK)

10 a $A = \pi r^2 = \pi \times \left(\frac{60}{2} \times 10^{-2}\right)^2 = 0.283\ \text{m}^2$ (1 MARK)

$R = \rho\frac{L}{A} \ \therefore 12 \times 10^{-6} = \rho \times \frac{2.4}{0.283}$ (1 MARK)

$\rho = 1.4 \times 10^{-6}\ \Omega\ \text{m}$ (1 MARK)

b $V = IR \ \therefore 900 = I \times 12 \times 10^{-6}$

$I = 7.5 \times 10^{7}\ \text{A}$ (1 MARK)

11 $V = IR = 40 \times 10^{-3} \times 90$ (1 MARK)

$V = 3.6\ \text{V}$ (1 MARK)

12 a D (1 MARK)

Given that R is constant as the device is ohmic, $V_i = I_i R$, so $R = \frac{V_i}{I_i} = \frac{3V_i}{3I_i}$

b C (1 MARK)

The resistance of the device does not affect the potential difference applied.

13 a $R = \frac{12}{2} = 6\ \Omega$ (1 MARK)

Area has changed by a factor of 2. Given $R = \rho\frac{L}{A}$, resistance will change by an inverse factor of the change in area (a factor of $\frac{1}{2}$).

b $R = 3 \times 12 = 36\ \Omega$ (1 MARK)

Length has changed by a factor of 3. Given $R = \rho\frac{L}{A}$, resistance will change by the same factor as length (a factor of 3).

14 $V = IR \ \therefore 60 = 3.0 \times R$

$R = 20\ \Omega$ (1 MARK)

Given the charger is ohmic, resistance is constant:

$V = IR \ \therefore 45 = I \times 20$

$I = 2.3\ \text{A}$ (1 MARK)

15 a Device P is ohmic. (1 MARK)

We know this because the plot is linear (with a constant gradient) and passes through the origin.

b Use any two points from the graph for P to calculate the gradient:

$gradient = \frac{rise}{run} = \frac{0.02 - 0}{5 - 0} = 0.004$ (1 MARK)

$\frac{1}{R} = gradient \ \therefore \frac{1}{R} = 0.004$ (1 MARK)

$R = 250\ \Omega$ (1 MARK)

c From the graph: when $V = 5.0\ \text{V}$, $I = 3.0\ \text{A}$

$V = IR \ \therefore 5.0 = 3.0 \times R$ (1 MARK)

$R = 1.67 = 1.7\ \Omega$ (1 MARK)

16 [Resistivity is the opposition of a material to the flow of current,[1]] [whereas resistance is the opposition of an object to the flow of current.[2]] [Resistivity depends on the material itself and the temperature,[3]] [while resistance depends on the material, temperature, and geometry of the object.[4]]

- I have explicitly addressed resistivity.[1]
- I have explicitly addressed resistance.[2]
- I have explicitly addressed the factors that affect resistivity.[3]
- I have explicitly addressed the factors that affect resistance.[4]

Previous lessons

17 $K = C + 273.15 = 1700 + 273.15 = 1973.15\ \text{K}$ (1 MARK)

$\lambda_{max} = \frac{b}{T} = \frac{2.89 \times 10^{-3}}{1973.15} = 1.46 \times 10^{-6}\ \text{m}$ (1 MARK)

This content was covered in Lesson 2A.

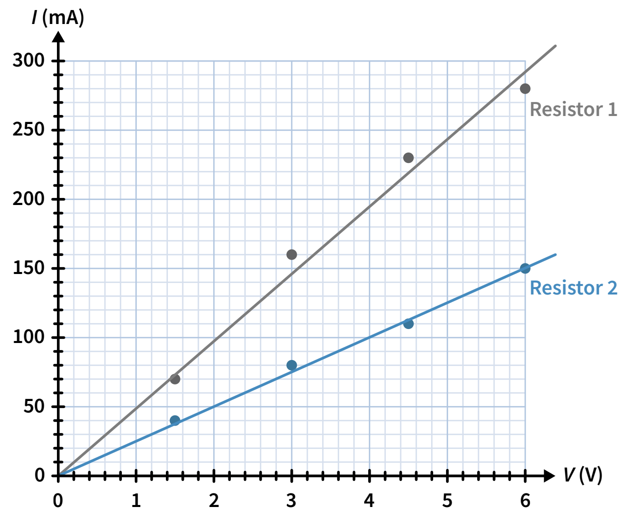
18 a Radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays. (1 MARK)

b Gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, radio waves. (1 MARK)

This content was covered in Lesson 3A.

Key science skills

19 a



- I have plotted potential difference on the horizontal axis and current on the vertical axis.
- I have included axis labels and appropriate units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each data point.
- I have included two lines of best fit.
- I have labelled each line of best fit with its corresponding resistor number.

4B

b Resistor 2 has a greater resistance. (1 MARK)

Note that the gradient of the I-V graph for a resistor (an ohmic device) represents $\frac{1}{R}$, so a smaller gradient corresponds to a greater resistance.

4C Series circuits

Theory review questions

1 I; III. Series connections are end to end.

2 C. Remember that $V_n \propto R_n$.

3 D. The sum of all load voltage drops equals the total supplied voltage.

4 V_1

5 B. Adding components adds resistance which decreases current for a constant voltage, decreasing total power.

Deconstructed exam-style question

6 **a** A

b C. $R_T = 200 + 400 + 100 = 700\ \Omega$

c B. $V_T = IR_T \ \therefore 14.0 = I \times 700$

$I = 2.00 \times 10^{-2}$ A

d B. $V_3 = IR_3 = 0.0200 \times 100 = 2.00$ V

e $R_T = 200 + 400 + 100 = 700\ \Omega$ (1 MARK)

$V_T = IR_T \ \therefore 14.0 = I \times 700$

$I = 2.00 \times 10^{-2}$ A (1 MARK)

$V_3 = IR_3 = 2.00 \times 10^{-2} \times 100 = 2.00$ V (1 MARK)

$P_3 = V_3 I = 2.00 \times 2.00 \times 10^{-2} = 4.00 \times 10^{-2}$ W (1 MARK)

Exam-style questions

This lesson

7 **a** $R_T = R_1 + R_2 + R_3 = 200 + 400 + 450 = 1050\ \Omega$ (1 MARK)

b $R_T = R_2 + R_3 = 400 + 450 = 850\ \Omega$ (1 MARK)

8 **a** $R_T = R_1 + R_2 = 10 + 20 = 30\ \Omega$ (1 MARK)

$V_T = IR_T \ \therefore 12 = I \times 30$

$I = 0.40$ A (1 MARK)

b $V_2 = IR_2 = 0.40 \times 20 = 8.0$ V (1 MARK)

9 $V_2 = IR_2 \ \therefore 4.0 = I \times 400$

$I = 0.010$ A (1 MARK)

$V_1 = IR_1 = 0.010 \times 200 = 2.0$ V (1 MARK)

$V_{supply} = V_1 + V_2 = 2.0 + 4.0 = 6.0$ V (1 MARK)

OR

$V_2 = IR_2 \ \therefore 4.0 = I \times 400$

$I = 0.010$ A (1 MARK)

$R_T = R_1 + R_2 = 200 + 400 = 600\ \Omega$ (1 MARK)

$V_{supply} = V_T = IR_T = 0.010 \times 600 = 6.0$ V (1 MARK)

OR

$R_T = 200 + 400 = 600\ \Omega$ (1 MARK)

$R_2 = \frac{2}{3} \times R_T$

$V_n \propto R_n \ \therefore V_2 = \frac{2}{3} \times V_{supply}$ (1 MARK)

$V_{supply} = \frac{3}{2} \times 4.0 = 6.0$ V (1 MARK)

10 $R_T = 4x$

$V_n \propto R_n$

$R_1 = x = \frac{1}{4}R_T \ \therefore V_1 = \frac{1}{4} \times V_T = \frac{1}{4} \times 20 = 5$ V (1 MARK)

$R_2 = 2x = \frac{2}{4}R_T \ \therefore V_2 = \frac{2}{4} \times V_T = \frac{1}{2} \times 20 = 10$ V (1 MARK)

$R_3 = x = \frac{1}{4}R_T \ \therefore V_3 = \frac{1}{4} \times V_T = \frac{1}{4} \times 20 = 5$ V (1 MARK)

11 Since the switch is open, no current flows.

$P_2 = V_2 I = 0$ W (1 MARK)

12 **a** $R_T = R_1 + R_2 + R_3 = 20 + 10 + 40 = 70\ \Omega$ (1 MARK)

$V_T = IR_T \ \therefore 20 = I \times 70$

$I = 0.286$ A (1 MARK)

$P_T = V_T I = 20 \times 0.286 = 5.7$ W (1 MARK)

b $V_3 = IR_3 = 0.286 \times 40 = 11.43$ V (1 MARK)

$P_3 = V_3 I = 11.43 \times 0.286 = 3.3$ W (1 MARK)

13 **a** $R_T = 1.0 \times 10^3 + 30 + 25 = 1055\ \Omega$ (1 MARK)

$V_T = 4 \times 1.5 = 6.0$ V

$V_T = IR_T \ \therefore 6.0 = I \times 1055$

$I = 0.0057$ A $= 5.7$ mA (1 MARK)

Since $I < 7.00$ mA, the remote control unit will not overheat. (1 MARK)

b $R_T = R_{new} + 30 + 25$ (1 MARK)

Let $I = 7.00$ mA to determine the resistance required to prevent overheating.

$V_T = IR_T \ \therefore 6.0 = 7.00 \times 10^{-3} \times (R_{new} + 30 + 25)$ (1 MARK)

$R_{new} = 802\ \Omega$ ∴ the minimum resistance that will still prevent overheating is the 810 Ω resistor. (1 MARK)

c $R_T = 1.0 \times 10^3 + 30 = 1030\ \Omega$ (1 MARK)

$V_T = 4 \times 1.5 + 0.33 = 6.33$ V

$V_T = IR_T \ \therefore 6.33 = I \times 1030$

$I = 0.00615$ A (1 MARK)

$P_{antenna} = V_{antenna} I = 0.33 \times 0.00615 = 0.0020$ W

$P_{antenna} = 2.0$ mW (1 MARK)

14 [Sione is correct, and Bruno is incorrect.[1]][Adding components increases the total resistance of the circuit.[2]][This decreases the current according to Ohm's law, which for a constant voltage causes a decrease in power use.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: equivalent resistance in series circuits.[2]
- I have used the relevant theory: power in series circuits.[3]

15 Using $V_n \propto R_n$, $P = VI$, and the fact that I is constant in a series circuit:

$P_n \propto R_n$ and $R_3 = \frac{1}{8} \times R_T \therefore P_3 = \frac{1}{8} \times P_T$ (1 MARK)

$P_3 = \frac{1}{8} \times 10 = 1.25$ W (1 MARK)

16 **a** $R_T = 200 + 150 + 50 = 400\ \Omega$ (1 MARK)

$V_T = 5.0 + 5.0 = 10.0$ V

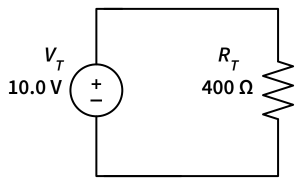
$V_T = IR_T \therefore 10.0 = I \times 400$

$I = 0.025$ A (1 MARK)

$P = VI = 5.0 \times 0.025 = 0.125$

The power delivered by each source is 0.13 W (1 MARK)

b



- I have drawn an equivalent circuit with one power source and one resistor.
- I have labelled each component correctly.
- I have included the correct value for each component.

c The power delivered by each source would not change. (1 MARK)

Note that the order of components in a series circuit does not affect the circuit behaviour.

Previous lessons

17 [Convection can occur in the mantle due to its high temperature and pressure.[1]][The convection in the mantle is very slow.[2]]

- I have explicitly addressed why convection can occur in the mantle.[1]
- I have explicitly addressed the speed of convection in the mantle.[2]

This content was covered in Lesson 3C.

18 1 hour = 60 × 60 = 3600 s

$P = \frac{E}{t} = \frac{7.2 \times 10^3}{3600} = 2.0$ W (1 MARK)

$P = VI \therefore 2.0 = V \times 1.0$

$V = 2.0$ V (1 MARK)

OR

$V = \frac{E}{Q}$ and $I = \frac{Q}{t} \therefore E = VIt$

1 hour = 60 × 60 = 3600 s

$7.2 \times 10^3 = V \times 1.0 \times 3600$ (1 MARK)

$V = 2.0$ V (1 MARK)

OR

1 hr = 60 × 60 = 3600 s

$I = \frac{Q}{t} \therefore 1.0 = \frac{Q}{3600}$

$Q = 3.6 \times 10^3$ C (1 MARK)

$V = \frac{E}{Q} = \frac{7.2 \times 10^3}{3.6 \times 10^3}$

$V = 2.0$ V (1 MARK)

This content was covered in Lesson 4A.

Key science skills

19 [Mahua should repeat the current measurement for each number of resistors multiple times and take the average.[1]][The effect of random error is reduced by taking an average of multiple measurements since the random errors in each measurement tend to cancel out.[2]]

- I have explicitly addressed a way to reduce the effects of random error.[1]
- I have used the relevant theory: random error.[2]

4D Parallel circuits

Theory review questions

1 II; IV

2 D. The voltage drop across a component in a parallel circuit is always the same.

3 C

4 to the same node; increases; stays the same

5 R_4, R_3, R_2, R_1. Power consumption is proportional to current and voltage. Voltage is equal for all resistors and current is inversely proportional to resistance.

6 C. There is still a closed path for a current to flow through (through the remaining bulbs).

7 Circuit 3, Circuit 1, Circuit 2

Deconstructed exam-style question

8 **a** A **b** C **c** A

d $\frac{1}{R_T} = \frac{1}{200} + \frac{1}{300} + \frac{1}{400}$

$R_T = 92.3\ \Omega$ (1 MARK)

$V_T = I_T R_T \therefore 240 = I_T \times 92.3$

$I_T = 2.60$ A

$P_T = V_T I_T = 240 \times 2.60 = 624$ W (1 MARK)

$V_{300\,\Omega} = I_{300\,\Omega} \times R_{300\,\Omega} \;\therefore 240 = I_{300\,\Omega} \times 300$

$I_{300\,\Omega} = 0.800$ A

$P_{300\,\Omega} = V_{300\,\Omega} \times I_{300\,\Omega} = 240 \times 0.800 = 192$ W (1 MARK)

$\frac{P_{300\,\Omega}}{P_T} = \frac{192}{624} = 0.308 = 30.8\ \%$ (1 MARK)

Exam-style questions

This lesson

9 **a** $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{600} + \frac{1}{400} + \frac{1}{800}$

$R_T = 184.6 = 185\ \Omega$ (1 MARK)

b $\frac{1}{R_T} = \frac{1}{R_4} + \frac{1}{R_5} = \frac{1}{100} + \frac{1}{100 \times 10^3}$

$R_T = 99.9 = 1.0 \times 10^2\ \Omega$ (1 MARK)

10 **a** $\frac{1}{R_T} = \frac{1}{50} + \frac{1}{100} + \frac{1}{50}$

$R_T = 20\ \Omega$ (1 MARK)

$V_T = I_T R_T \;\therefore 9 = I_T \times 20$

$I_T = 0.45 = 0.5$ A (1 MARK)

b $V = IR \;\therefore 9 = I_{100\,\Omega} \times 100$ (1 MARK)

$I_{100\,\Omega} = 0.09$ A (1 MARK)

11 $I_n \propto \frac{1}{R_n} \;\therefore I_1 = 4 \times I_2 \;\therefore I_T = I_1 + I_2 = 5 \times I_2$

$I_2 = \frac{1}{5} \times I_T = \frac{1}{5} \times 5.0$ (1 MARK)

$I_2 = 1.0$ A (1 MARK)

12 **a** $\frac{1}{R_T} = \frac{1}{20} + \frac{1}{40} + \frac{1}{20}$

$R_T = 8.0\ \Omega$ (1 MARK)

$V_T = I_T R_T \;\therefore 9.0 = I_T \times 8.0$

$I_T = 1.13$ A (1 MARK)

$P_T = V_T I_T = 9.0 \times 1.13$

$P_T = 10$ W (1 MARK)

b $V_T = 9.0 = I_{20\,\Omega} \times 20$

$I_{20\,\Omega} = 0.45$ A (1 MARK)

$P_{20\,\Omega} = V_T I_{20\,\Omega} = 9.0 \times 0.45 = 4.05$ W

Power dissipated by the two 20 Ω resistors is $2 \times P_{20\,\Omega} = 2 \times 4.05 = 8.1$ W. (1 MARK)

13 [Joanne should choose the set with fewer bulbs.[1]][In parallel circuits, adding more components (in this case bulbs) draws more current and thus uses more power, so the set with fewer bulbs will use less power.[2]]

- I have explicitly addressed which set of lights Joanne should choose.[1]
- I have used the relevant theory: power in parallel circuits.[2]

14 [The voltage provided to the toy circuit is the same (1.5 V) in both setups,[1]] [since connecting two equal sources in parallel does not affect the total voltage.[2]][The total current provided to the toy circuit is equal in both setups,[3]][and is determined by Ohm's law, $V = IR$, where $V = 1.5$ V.[4]] [However, in the two-cell setup, the current provided by each cell is half the current provided by the cell in the single-cell setup.[5]]

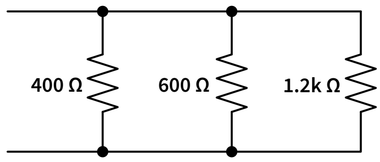
- I have explicitly addressed the voltage provided to the circuit in both setups.[1]
- I have used the relevant theory: voltage in parallel circuits.[2]
- I have explicitly addressed the current provided to the circuit in both setups.[3]
- I have used the relevant theory: Ohm's law.[4]
- I have explicitly addressed the current provided by each cell in the two-cell setup.[5]

15 The power consumption would increase to infinity. (1 MARK)

Note that this is because power consumption increases each time another arm is added, so adding infinite arms would give infinite power consumption. Obviously this is not physically possible.

16 For a 200 Ω resistor: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots = \frac{1}{200}$

$\frac{1}{400} + \frac{1}{600} + \frac{1}{1200} = \frac{6}{1200} = \frac{1}{200}$ (1 MARK)



- I have drawn resistors connected in parallel.
- I have selected resistor values that have an equivalent resistance of 200 Ω.

Previous lessons

17 The driving factor behind the energy flows at the Earth's surface is the imbalance in incoming solar radiation. (1 MARK)

This content was covered in Lesson 3C.

18 **a** $V = IR \;\therefore 240 = 10 \times R$

$R = 24\ \Omega$ (1 MARK)

b $R = \rho\frac{L}{A} \;\therefore 24 = \rho \times \frac{2.0 \times 10^{-2}}{1.0 \times 10^{-6}}$ (1 MARK)

$\rho = 1.2 \times 10^{-3}\ \Omega$ m (1 MARK)

This content was covered in Lesson 4B.

Key science skills

19 Independent: number of 1 kΩ resistors (1 MARK)

Dependent: total current (1 MARK)

Controlled: source voltage **OR** ammeter connection (1 MARK)

4E Combining series and parallel circuits

Theory review questions

1 *S*-series; *T*-parallel; *U*-parallel; *V*-series

2

Step no.	Action
2	Find total equivalent resistance of the circuit
1	Find the equivalent resistance of the parallel resistors
4	Find the current passing through R_4 using Ohm's law or $I_n \propto \frac{1}{R_n}$
3	Find the total current using Ohm's law

3 A

Deconstructed exam-style question

4 **a** B **b** C **c** A

d $R_T = R_1 + (R_2 || R_3) + R_4 = 100 + \left(\frac{1}{400} + \frac{1}{400}\right)^{-1} + 30.0 = 330\ \Omega$ (1 MARK)

$V_4 = \frac{R_4}{R_T} \times V_T = \frac{30.0}{330} \times 230 = 20.9\ \text{V}$ (1 MARK)

$I_4 = I_T = \frac{V_T}{R_T} = \frac{230}{330} = 0.697\ \text{A}$ (1 MARK)

$P_4 = V_4 I_4 = 20.9 \times 0.697 = 14.6\ \text{W}$ (1 MARK)

OR

$R_T = R_1 + (R_2 || R_3) + R_4 = 100 + \left(\frac{1}{400} + \frac{1}{400}\right)^{-1} + 30.0 = 330\ \Omega$ (1 MARK)

$I_4 = I_T = \frac{V_T}{R_T} = \frac{230}{330} = 0.697\ \text{A}$ (1 MARK)

$V_4 = I_4 R_4 = 0.697 \times 30.0 = 20.9\ \text{V}$ (1 MARK)

$P_4 = V_4 I_4 = 20.9 \times 0.697 = 14.6\ \text{W}$ (1 MARK)

OR

$R_T = R_1 + (R_2 || R_3) + R_4 = 100 + \left(\frac{1}{400} + \frac{1}{400}\right)^{-1} + 30.0 = 330\ \Omega$ (1 MARK)

$V_4 = \frac{R_4}{R_T} \times V_T = \frac{30.0}{330} \times 230 = 20.9\ \text{V}$ (1 MARK)

$I_4 = \frac{V_4}{R_4} = \frac{20.9}{30.0} = 0.697\ \text{A}$ (1 MARK)

$P_4 = V_4 I_4 = 20.9 \times 0.697 = 14.6\ \text{W}$ (1 MARK)

Exam-style questions

This lesson

5 **a** $R_T = R_1 + (R_2 + R_3) || (R_4 + (R_5 || (R_6 + R_7)))$ (1 MARK)

$R_2 + R_3 = 7.0 + 3.0 = 10.0\ \Omega$

$R_5 || (R_6 + R_7) = \left(\frac{1}{8.0} + \frac{1}{4.0 + 4.0}\right)^{-1} = 4.0\ \Omega$

$R_4 + (R_5 || (R_6 + R_7)) = 5.0 + 4.0 = 9.0\ \Omega$

$R_T = 5.0 + \left(\frac{1}{10.0} + \frac{1}{9.0}\right)^{-1} = 9.7\ \Omega$ (1 MARK)

b $R_T = R_1 + (R_2 + R_3) || ((R_4 || R_5) + R_6)$ (1 MARK)

$R_2 + R_3 = 200 + 50 = 250\ \Omega$

$R_4 || R_5 = \left(\frac{1}{20} + \frac{1}{60}\right)^{-1} = 15\ \Omega$

$(R_4 || R_5) + R_6 = 15 + 50 = 65\ \Omega$

$R_T = 30 + \left(\frac{1}{250} + \frac{1}{65}\right)^{-1} = 82\ \Omega$ (1 MARK)

c $R_T = (R_1 || R_2) + (R_3 || R_4)$ (1 MARK)

$R_1 || R_2 = \left(\frac{1}{200} + \frac{1}{600}\right)^{-1} = 150\ \Omega$

$R_3 || R_4 = \left(\frac{1}{30} + \frac{1}{70}\right)^{-1} = 21\ \Omega$

$R_T = 150 + 21 = 171\ \Omega$ (1 MARK)

6 $R_T = R_1 + R_2 || (R_3 + R_4) + R_5$ (1 MARK)

$R_{||} = R_2 || (R_3 + R_4) = \left(\frac{1}{10} + \frac{1}{15 + 15}\right)^{-1} = 7.5\ \Omega$

$R_T = 7.5 + 7.5 + 15 = 30\ \Omega$ (1 MARK)

$V_1 = \frac{R_1}{R_T} \times V_T = \frac{7.5}{30} \times 30 = 7.5\ \text{V}$ (1 MARK)

$V_{||} = \frac{R_{||}}{R_T} \times V_T = \frac{7.5}{30} \times 30 = 7.5\ \text{V}$

$V_4 = \frac{R_4}{R_3 + R_4} \times V_{||} = \frac{15}{15 + 15} \times 7.5 = 3.8\ \text{V}$ (1 MARK)

7 $V_{||} = V_1 = I_1 R_1 = 1.0 \times 12 = 12\ \text{V}$ (1 MARK)

$V_{3\,\&\,4} = V_T - V_{||} = 48 - 12 = 36\ \text{V}$

$V_3 = \frac{R_3}{R_3 + R_4} \times V_{3\,\&\,4} = \frac{10}{10 + 14} \times 36 = 15\ \text{V}$ (1 MARK)

$I_T = I_3 = \frac{V_3}{R_3} = \frac{15}{10} = 1.5\ \text{A}$ (1 MARK)

$I_2 = I_{||} - I_1 = 1.5 - 1.0 = 0.5\ \text{A}$ (1 MARK)

$R_2 = \frac{V_2}{I_2} = \frac{V_{||}}{I_2} = \frac{12}{0.5} = 24\ \Omega$ (1 MARK)

OR

$V_{||} = V_1 = I_1 R_1 = 1.0 \times 12 = 12\ \text{V}$ (1 MARK)

$V_{3\,\&\,4} = V_T - V_{||} = 48 - 12 = 36\ \text{V}$

$V_3 = \frac{R_3}{R_3 + R_4} \times V_{3\,\&\,4} = \frac{10}{10 + 14} \times 36 = 15\ \text{V}$ (1 MARK)

$I_T = I_3 = \frac{V_3}{R_3} = \frac{15}{10} = 1.5\ \text{A}$ (1 MARK)

$I_T = I_{||}\ \therefore R_{||} = \frac{V_{||}}{I_T} = \frac{12}{1.5} = 8.0\ \Omega$ (1 MARK)

$\frac{1}{R_{||}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{12} + \frac{1}{R_2} = \frac{1}{8.0}$

$R_2 = 24\ \Omega$ (1 MARK)

8 $R_{||} = R_2||(R_3 + R_4) = \left(\frac{1}{30} + \frac{1}{2.0 \times 10^3 + 10}\right)^{-1} = 30\ \Omega$

$R_T = R_1 + R_{||} + R_5 = 20 + 30 + 15 = 65\ \Omega$

$V_1 = \frac{R_1}{R_T} \times V_T = \frac{20}{65} \times 120 = 37\ \text{V}$ (1 MARK)

$V_2 = V_{||} = \frac{R_{||}}{R_T} \times V_T = \frac{30}{65} \times 120 = 55\ \text{V}$ (1 MARK)

$V_5 = \frac{R_5}{R_T} \times V_T = \frac{15}{65} \times 120 = 28\ \text{V}$ (1 MARK)

Since R_2 has a much smaller resistance than $R_3 + R_4$, almost all of the total current will flow through R_2. Since $P = VI$, and each of R_1, R_2, and R_5 all have approximately equal current flowing through them, the resistor with the highest voltage drop will consume the most power. (1 MARK)

Therefore, R_2 will consume the most power. (1 MARK)

OR

$R_{||} = R_2||(R_3 + R_4) = \left(\frac{1}{30} + \frac{1}{2.0 \times 10^3 + 10}\right)^{-1} = 30\ \Omega$

$R_T = R_1 + R_{||} + R_5 = 20 + 30 + 15 = 65\ \Omega$

$V_1 = \frac{R_1}{R_T} \times V_T = \frac{20}{65} \times 120 = 37\ \text{V}$ (1 MARK)

$V_2 = V_{||} = \frac{R_{||}}{R_T} \times V_T = \frac{30}{65} \times 120 = 55\ \text{V}$ (1 MARK)

$V_5 = \frac{R_5}{R_T} \times V_T = \frac{15}{65} \times 120 = 28\ \text{V}$ (1 MARK)

$I_1 = \frac{V_1}{R_1} = \frac{37}{20} = 1.85\ \text{A}$

$I_2 = \frac{V_2}{R_2} = \frac{55}{30} = 1.85\ \text{A}$

$I_5 = I_1 = 1.85\ \text{A}$

Since R_4 has very high resistance, I_3 and I_4 will be small so P_3 and P_4 will be small.

$P_1 = V_1 I_1 = 37 \times 1.85 = 68\ \text{W}$

$P_2 = V_2 I_2 = 55 \times 1.85 = 1.0 \times 10^2\ \text{W}$ (1 MARK)

$P_5 = V_5 I_5 = 28 \times 1.85 = 52\ \text{W}$

Therefore, R_2 will consume the most power. (1 MARK)

Previous lessons

9 [During summer.[1]][This is due to the tilt of the Earth during summer in the Southern Hemisphere, angling Australia more towards the Sun.[2]]

- I have explicitly addressed the season in which Australia receives the greatest intensity of solar radiation.[1]
- I have used the relevant theory: radiation in the atmosphere.[2]

This content was covered in lesson 3C.

10 $R_T = R_1 + R_2 + R_3 = 10 + 30 + 5.0 = 45.0\ \Omega$ (1 MARK)

$I_T = \frac{V_T}{R_T} = \frac{9}{45.0} = 0.2\ \text{A}$ (1 MARK)

This content was covered in lesson 4C.

Key science skills

11 [Experiment 1 has the more precise and the more accurate results.[1]] [The results from experiment 1 have an average (5.54 mA) closer to the actual current (5.5 mA) than the average of experiment 2 (5.64 mA).[2]] [The results from experiment 1 have a smaller range (0.2 mA) than the results of experiment 2 (0.8 mA).[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: the definition of accuracy.[2]
- I have used the relevant theory: the definition of precision.[3]
- I have used the provided data in my answer.

Chapter 4 Review

Section A

1 B

2 B

$P = VI\ \therefore 45 = 240 \times I\ \therefore I = 0.1875\ \text{A}$

Per second, $Q = I \times t = 0.1875 \times 1 = 0.1875\ \text{C}$

$n_e = \frac{-Q}{-e} = \frac{-0.1875}{-1.60 \times 10^{-19}} = 1.172 \times 10^{18} = 1.2 \times 10^{18}$ electrons

OR

$E = P \times t = 45 \times 1 = 45\ \text{J}$

$V = \frac{E}{Q}\ \therefore 240 = \frac{45}{Q}$

$Q = 0.1875\ \text{C}$

$n_e = \frac{-Q}{-e} = \frac{-0.1875}{-1.60 \times 10^{-19}} = 1.172 \times 10^{18} = 1.2 \times 10^{18}$ electrons

3 A. The voltage drop across each resistor remains at 15 V (the supply voltage) both when in series and in parallel. Adding a resistor in parallel will decrease the total resistance and therefore increase the total current in the circuit.

4 C. The equivalent resistance of parallel resistors is always smaller than the smallest resistance of an individual arm.

5 D

$\frac{1}{R_A} = \frac{1}{3+3} + \frac{1}{6} = \frac{1}{3}\ \therefore R_A = 3\ \Omega$

$R_T = 11 = R_A + R_B = 3 + R_B\ \therefore R_B = 8\ \Omega$

$\frac{1}{R_B} = \frac{1}{10+10} + \frac{1}{X}\ \therefore \frac{1}{8} = \frac{1}{20} + \frac{1}{X}$

$X = 40\ \Omega$

Section B

6 **a** $R = \rho\frac{L}{A}\ \therefore 8.00 \times 10^4 = 640 \times \frac{1.20 \times 10^{-2}}{A}$

$A = 9.60 \times 10^{-5}\ \text{m}^2$ (1 MARK)

A cylinder's cross section is a circle, so $A = \pi r^2\ \therefore 9.6 \times 10^{-5} = \pi r^2$

$r = 5.528 \times 10^{-3}\ \text{m} = 0.553\ \text{cm}$ (1 MARK)

b $V = IR \therefore 35.0 = I \times 8.00 \times 10^4$

$I = 4.375 \times 10^{-4}$ A (1 MARK)

$P = VI = 35.0 \times 4.375 \times 10^{-4}$ W (1 MARK)

$P = 1.53 \times 10^{-2}$ W

c $P = \frac{E}{t} \therefore 1.53 \times 10^{-2} = \frac{E}{600}$

$E = 9.18$ J (1 MARK)

$Q = mc\Delta T = 5 \times 10^{-3} \times 753 \times \Delta T$

Resistors convert electric potential energy into thermal energy, so in this case $E = Q$

$E = Q \therefore 9.18 = 5 \times 10^{-3} \times 753 \times \Delta T$ (1 MARK)

$\Delta T = 2.438 = 2$ K (or °C) (1 MARK)

7 [Both students are able to determine the total power usage of the circuit.[1]] [Since $P = VI$, determining the power usage across elements requires the voltage and current used by those elements.[2]] [Erin is able to determine the power provided by the battery, and Jack is able to determine the power used by the circuit elements.[3]] [The power provided by the battery is equal to the power used by the circuit elements, so they both can calculate the total power usage.[4]]

- I have explicitly addressed whether each student can determine the total power usage of the circuit.[1]
- I have used the relevant theory: measuring the power used by circuit elements.[2]
- I have referred to the elements that the students are measuring.[3]
- I have related my answer to the context of the question.[4]

8 Consider the parallel circuit of the 100 Ω and 200 Ω resistors:

$R_1 = \left(\frac{1}{100} + \frac{1}{200}\right)^{-1} = 66.67\ \Omega$ (1 MARK)

Consider the parallel circuit of R_1 and the two 300 Ω resistors:

$R_2 = \left(\frac{1}{66.7} + \frac{1}{300 + 300}\right)^{-1} = 60\ \Omega$ (1 MARK)

Consider the parallel circuit of the 400 Ω and 500 Ω resistors:

$R_3 = \left(\frac{1}{400} + \frac{1}{500}\right)^{-1} = 222.22\ \Omega$ (1 MARK)

Consider the parallel circuit of R_2 and R_3:

$R_T = \left(\frac{1}{222.22} + \frac{1}{60}\right)^{-1} = 47.2\ \Omega$ (1 MARK)

Therefore the equivalent resistance between X and Y is 47.2 Ω.

9 **a** $R_2 : R_3 = 600:200 = 3:1$

$I_n \propto \frac{1}{R_n} \therefore I_2 : I_3 = 1:3$ (1 MARK)

$I_T = I_2 + I_3 \therefore I_2 = \frac{1}{4} I_T$ and $I_3 = \frac{3}{4} I_T$

So, $I_X : I_Y = I_2 : I_T = 1:4$ (1 MARK)

b $R_{||} = \left(\frac{1}{600} + \frac{1}{200}\right)^{-1} = 150\ \Omega$ (1 MARK)

$I_T = \frac{V_T}{R_T} = \frac{12.0}{400 + 150} = 0.0218$ A (1 MARK)

$V_1 = I_1 R_1 = 0.0218 \times 400 = 8.73$ V (1 MARK)

OR

$R_{||} = \left(\frac{1}{600} + \frac{1}{200}\right)^{-1} = 150\ \Omega$ (1 MARK)

$R_T = R_1 + R_{||} = 400 + 150 = 550$ (1 MARK)

$V_1 = \frac{R_1}{R_T} \times V_T = \frac{400}{550} \times 12.0 = 8.73$ V (1 MARK)

c $V_T = V_1 + V_3 \therefore 12.0 = 8.73 + V_3$

$V_3 = 3.27$ V (1 MARK)

$I_T = \frac{V_T}{R_T} = \frac{12.0}{400 + 150} = 0.0218$ A

Since $I_X : I_Y = 1:4$, $I_3 = \frac{3}{4} I_T = \frac{3}{4} \times 0.0218 = 0.0164$ A (1 MARK)

$P_3 = V_3 I_3 = 3.27 \times 0.0164 = 0.0535$ W (1 MARK)

d $R_T = 550 + R_L$ (1 MARK)

$I_T = \frac{V_T}{R_T} = \frac{12.0}{550 + R_L}$ (1 MARK)

Current through A_Y is equal to I_T, so $\frac{12.0}{550 + R_L} = 15 \times 10^{-3}$

$R_L = 250\ \Omega$ (1 MARK)

REVIEW

5A Applications of electric circuits

Theory review questions

1 I; III

2 A

3 B. The choice of the variable resistor as R_1 or R_2 depends on the characteristics of the variable resistor and the desired output voltage behaviour.

4 real; maximum; significant

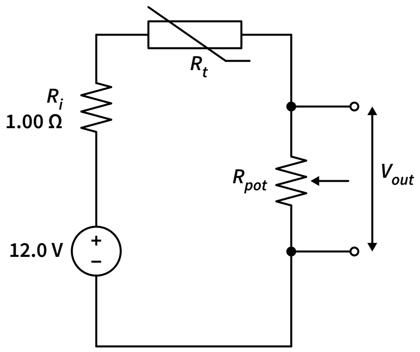
5 B. This answer can be found using the voltage divider equation $\left(\frac{20}{20+40} \times V_{in}\right)$ or the proportionality of voltage to resistance in series circuits.

Deconstructed exam-style question

6 **a** B **b** B **c** D

d Need output voltage to increase with temperature, so make the thermistor R_1. (1 MARK)

Circuit design:



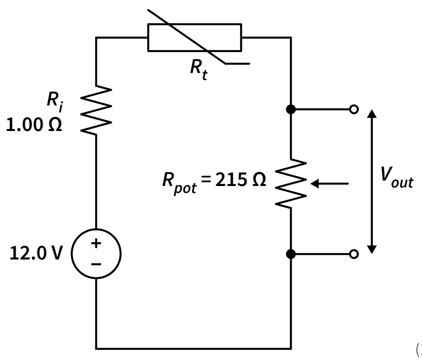
At 24°C, $R_t = 300\ \Omega$, $V_{out} = 5.00$ V

Since the battery has internal resistance:

$$V_{out} = \frac{R_{pot}}{(R_i + R_t) + R_{pot}} \times 12.0 = 5.00 \text{ V} \quad \text{(1 MARK)}$$

$$\frac{R_{pot}}{(1.00+300) + R_{pot}} \times 12.0 = 5.00 \quad \therefore R_{pot} = 215\ \Omega \quad \text{(1 MARK)}$$

Final circuit:



(1 MARK)

Exam-style questions

This lesson

7 $V_R = 5.0 - 2.0 = 3.0$ V (1 MARK)

$$I_{max} = \frac{V_R}{R_{min}} \quad \therefore 20 \times 10^{-3} = \frac{3.0}{R_{min}}$$

$R_{min} = 1.5 \times 10^2\ \Omega$ (1 MARK)

8 At 900 lux, $R_{LDR} = 20\ \Omega$ (1 MARK)

Since the threshold voltage is met, $V_{LED} = 2.0$ V (1 MARK)

Treat R_1 and the LDR as a voltage divider:

$$V_{LDR} = \frac{R_{LDR}}{R_1 + R_{LDR}} \times V_{in} = \frac{20}{20+20} \times (50 - 2.0) \quad \text{(1 MARK)}$$

$V_{LDR} = 24$ V (1 MARK)

9 $I = 0$ A (1 MARK)

There is no current through the thermistor due to the orientation of the diode in the thermistor arm.

10 [The voltage provided by a source with an internal resistance is smaller than an ideal source of the same voltage.[1]][The internal resistance limits the maximum current a source can provide, unlike an ideal source which has no maximum current.[2]]

I have explicitly addressed the effect of internal resistance on the voltage supplied by a source.[1]

I have explicitly addressed the effect of internal resistance on the current supplied by a source.[2]

11 Parallel resistors: $R_{||} = \left(\frac{1}{100} + \frac{1}{100}\right)^{-1} = 50\ \Omega$

$R_T = R_{||} + R_{therm} = 50 + R_{therm}$ (1 MARK)

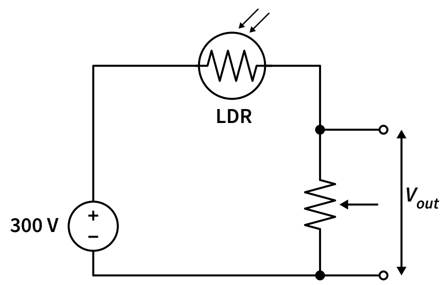
$V_T = I_T R_T \quad \therefore 7.0 = 100 \times 10^{-3} \times (50 + R_{therm})$

$R_{therm} = 20\ \Omega$ (1 MARK)

Using the graph, for $R_{therm} = 20\ \Omega$, T = 5°C (1 MARK)

12 Since R_{LDR} decreases with intensity, make the LDR R_1 of a voltage divider. (1 MARK)

Circuit design:

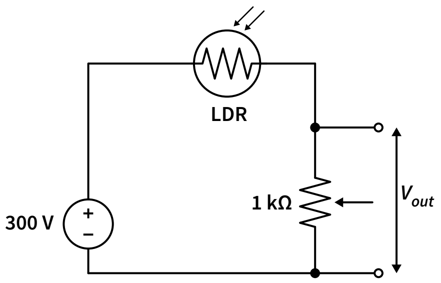


At 500 lux, $R_{LDR} = 2 \times 10^3\ \Omega$, $V_{out} = 100$ V

$$V_{out} = \frac{R_{pot}}{R_{LDR} + R_{pot}} \times 300 = 100 \text{ V} \quad \text{(1 MARK)}$$

$$\frac{R_{pot}}{2 \times 10^3 + R_{pot}} \times 300 = 100 \quad \therefore R_{pot} = 1000\ \Omega = 1\ \text{k}\Omega \quad \text{(1 MARK)}$$

Final circuit:



(1 MARK)

Previous lessons

13 [Solar radiation is mostly transmitted when it interacts with greenhouse gases.[1]][More of Earth's radiation is absorbed (and re-emitted) by greenhouse gases than solar radiation.[2]]

- I have explicitly addressed the interaction between solar radiation and greenhouse gases.[1]
- I have explicitly addressed the interaction between Earth's radiation and greenhouse gases.[2]

This content was covered in Lesson 3D.

14 $\frac{1}{R_T} = \frac{1}{20} + \frac{1}{100} + \frac{1}{40} + \frac{1}{40}$ (1 MARK)

$R_T = 9.1\ \Omega$ (1 MARK)

This content was covered in Lesson 4D.

Key science skills

15 [For an experiment to be valid, it needs to actually measure what it intends to measure.[1]][The stages of an experiment that contribute to validity are experimental design, conduction, and how the results are processed and analysed.[2]]

- I have explicitly addressed what it means for an experiment to be valid.[1]
- I have used the relevant theory: experimental stages affecting validity.[2]

5B Household electricity

Theory review questions

1 A. A kilowatt is a unit for power and an hour is a unit for time. A kilowatt-hour is a unit for the product of these two quantities: *power × time = energy*.

2 B. $E = P \times t = 3.0 \times 2.0 = 6.0$ kW h

3 C. 1 kW h $= 3.6 \times 10^6$ J so 2.0 kW h $= 2.0 \times 3.6 \times 10^6 = 7.2 \times 10^6$ J

4 C

5 A. Since the potential of the active wire changes between a positive and a negative value, the direction of current changes too.

6 A. The RMS value has the same magnitude as the DC value that delivers the equivalent average power. $V_{RMS} = \frac{1}{\sqrt{2}} \times V_{peak}$.

7 B

Deconstructed exam-style question

8 **a** A **b** C **c** B

d $V_{RMS} = \frac{1}{\sqrt{2}} \times V_{peak} = \frac{1}{\sqrt{2}} \times 300 = 212$ V (1 MARK)

$P = \frac{V_{RMS}^2}{R} = \frac{212^2}{80} = 562.5$ W $= 0.5625$ kW (1 MARK)

$E = P \times t = 0.5625 \times 4.0 = 2.25 = 2.3$ kW h (1 MARK)

Exam-style questions

This lesson

9 **a** 6.0 minutes = 0.10 hours

$P = \frac{E}{t} = \frac{0.16 \text{ kW h}}{0.10 \text{ h}}$ (1 MARK)

$P = 1.6$ kW (1 MARK)

b 0.16 kW h $= 0.16 \times 3.6 \times 10^6$ J $= 5.8 \times 10^5$ J (1 MARK)

10 From the graph, $V_{peak} = 3.5 \times 0.4 = 1.4$ V (1 MARK)

$V_{RMS} = \frac{1}{\sqrt{2}} \times V_{peak} = \frac{1}{\sqrt{2}} \times 1.4 = 0.99$ V (1 MARK)

11 [The only way to use the lights would be to have them all switched on at once, since a single break in the series circuit would prevent current flowing to any of them.[1]][They would also all glow much more dimly because the effective resistance of the circuit would be much larger than when connected in parallel (the voltage would need to be divided between the lights).[2]]

- I have used the relevant theory: current in series.[1]
- I have used the relevant theory: resistance in series.[2]

12 **a** $P = I_{RMS}^2 R \therefore 242 = I_{RMS}^2 \times 50$ (1 MARK)

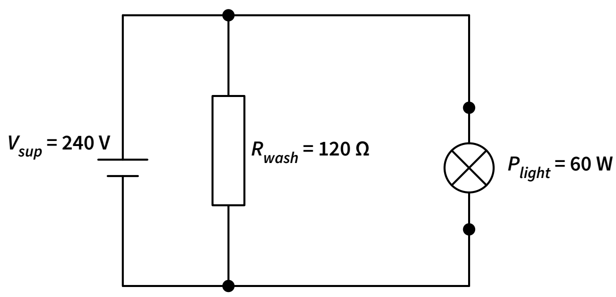
$I_{RMS} = \sqrt{\frac{242}{50}} = 2.2$ A (1 MARK)

b $I_{peak} = I_{RMS} \times \sqrt{2} = 2.2 \times \sqrt{2} = 3.1$ A (1 MARK)

c $E = P \times t = 0.242 \times 2.5$ (1 MARK)

$E = 0.605 = 0.61$ kW h (1 MARK)

13 **a**



- I have drawn a complete circuit diagram with a resistor and a light bulb connected to a power supply in parallel.[1]
- I have shown the voltage of the power supply.[2]
- I have shown the resistance of the washing machine (represented by a resistor).[3]
- I have shown the power of the light bulb.[4]

b Consider the washing machine:

$$I_{wash} = \frac{V_{sup}}{R_{wash}} = \frac{240}{120} = 2.00 \text{ A}$$ (1 MARK)

Consider the light bulb:

$$P_{light} = V_{sup} I_{light} \therefore 60 = 240 \times I_{light} \therefore I_{light} = 0.25 \text{ A}$$ (1 MARK)

$$I_{sup} = I_{wash} + I_{light} = 2.00 + 0.25 = 2.25 \text{ A}$$ (1 MARK)

Previous lessons

14 **a** [A correlation suggests that changes in one variable (such as temperature) occur at a similar time and in a similar way as changes in another variable (such as carbon dioxide levels).[1]] [But a correlation, by itself, does not indicate which variable is the explanatory/independent variable and which is the response/dependent variable, or whether both variables are responding to a change in a third variable.[2]]

- I have explicitly addressed the meaning of 'correlation'.[1]
- I have explicitly addressed why a correlation does not indicate causation.[2]

b [There is positive feedback between the two variables,[1]] [which means that an increase in carbon dioxide levels causes an increase in global temperatures[2]] [and an increase in global temperatures also causes an increase in carbon dioxide levels.[3]]

- I have explicitly addressed the feedback relationship between carbon dioxide levels and global temperatures.[1]
- I have used the relevant theory: how carbon dioxide levels affect global temperatures.[2]
- I have used the relevant theory: how global temperatures affect carbon dioxide levels.[3]

c [There has been a sudden and dramatic increase in atmospheric carbon dioxide levels[1]] [and global temperatures in the last 200 years.[2]] [This period coincides with humans burning a lot of fossil fuels, which is well understood to release carbon dioxide. Given the known effect carbon dioxide has on temperature, the data indicates this release of carbon is responsible for the increase in global temperatures.[3]]

- I have explicitly addressed the recent data regarding carbon dioxide levels.[1]
- I have explicitly addressed the recent data regarding global temperatures.[2]
- I have explicitly addressed the role of recent human activity.[3]

This content was covered in Lesson 3E.

15 **a** Consider the parallel section of the circuit with R_3 and R_4:

$$R_{||} = R_3 \| R_4 = \left(\frac{1}{3.0} + \frac{1}{6.0}\right)^{-1} = 2.0\ \Omega$$ (1 MARK)

Consider the series connections between R_1, R_2, and the parallel section:

$$R_T = R_1 + R_2 + R_{||} = 3.0 + 5.0 + 2.0 = 10.0\ \Omega$$ (1 MARK)

b Calculate the total current in the circuit:

$$I_T = \frac{V_T}{R_T} = \frac{20}{10.0} = 2.0 \text{ A}$$ (1 MARK)

Consider the parallel section of the circuit with R_3 and R_4:

$$V_{||} = I_T \times R_{||} = 2.0 \times 2.0 = 4.0 \text{ V}$$ (1 MARK)

Consider R_4 only:

$$I_{R4} = \frac{V_{||}}{R_4} = \frac{4.0}{6.0} = 0.67 \text{ A}$$ (1 MARK)

This content was covered in Lesson 4E.

Key science skills

16 **a** [Arden's data is more accurate[1]] [because the average of her data $\left(\frac{0.18 + 0.18 + 0.20 + 0.20 + 0.18}{5} = 0.19 \text{ to two significant figures}\right)$ is closer to the true value than Jacinta's data $\left(\frac{0.15 + 0.23 + 0.25 + 0.19 + 0.19}{5} = 0.20 \text{ to two significant figures}\right)$.[2]]

- I have explicitly addressed which data set is more accurate.[1]
- I have justified my answer with relevant data.[2]

b [Arden's data is more precise[1]] [because the range of her data (0.20 − 0.18 = 0.02) is smaller than the range of Jactina's data (0.25 − 0.15 = 0.10).[2]]

- I have explicitly addressed which data set is more precise.[1]
- I have justified my answer with relevant data.[2]

5C Electrical safety

Theory review questions

1 B. A fuse must be part of the normal circuit in order for it to melt if the current is too high and for it to cause a break in the circuit when it melts.

2 B. A fuse prevents too much current flowing within a circuit, which could otherwise cause a fire or damage appliances.

3 A

4 B. A fuse is designed to melt when there is too much current.

5 A. Circuit breakers measure the current and open a resettable switch when the current is too high.

6 A. Current does not get 'used up'. It must flow somewhere.

7 B

8 A. If the current in the active and neutral wires is different, then it is probably flowing somewhere unintended such as through a person. This is what the RCD is designed to prevent.

9 A. The earth wire provides a connection from the exterior of an appliance to the source, which would only carry current if the exterior of the appliance becomes live.

10 B. Voltage and resistance both affect the amount of current but, by itself, current is the measurement that corresponds to the severity of a shock.

Deconstructed exam-style question

11 a C. Current is leaving the intended circuit via the knife/Regina.

b A **c** C **d** B

e [The RCD is most likely to protect Regina.[1]][It will detect a difference between the currents flowing in the active wire and the neutral wire[2]] [and then switch the circuit off.[3]]

- I have explicitly addressed which safety design will protect Regina.[1]
- I have used the relevant theory: what triggers an RCD.[2]
- I have used the relevant theory: what happens when an RCD is triggered.[3]

Exam-style questions

This lesson

12 [The earth wire is designed for this situation[1]][to protect people against electric shock.[2]]

- I have explicitly addressed which safety feature is designed for this situation.[1]
- I have explicitly addressed what hazard is caused by this situation.[2]

13 a [Polly's conclusion is incorrect: a short circuit is not a shock hazard.[1]] [A short circuit reduces the resistance of the circuit so that the current in the circuit is greater,[2]][but this does not necessarily increase the chance of current flowing through a person to cause an electric shock.[3]]

- I have explicitly addressed whether Polly's conclusion is correct.[1]
- I have used the relevant theory: short circuits.[2]
- I have used the relevant theory: cause of electric shock.[3]

b [An RCD switches off a circuit only when there is a difference between the currents flowing in the active and neutral wires.[1]] [A short circuit provides a lower resistance path between the active and neutral wires but not an alternative path to either of the wires so they will carry the same current as each other.[2]]

- I have used the relevant theory: how an RCD works.[1]
- I have used the relevant theory: short circuits.[2]

14 a [A fuse or circuit breaker will cause a break in the circuit only if the current exceeds the intended value of that circuit, which will happen only if the resistance of the new pathway via the earth connection is low enough.[1]][The fuse or circuit breaker is designed to protect against overheating which can cause fires and damage to appliances.[2]]

- I have used the relevant theory: conditions that would cause a break in the circuit.[1]
- I have explicitly addressed the hazard that a fuse/circuit breaker protects against.[2]

b [An RCD should break the circuit in this case because current is leaving the circuit via the earth wire which means there will be a difference between the currents in the active and neutral wires.[1]] [An RCD protects against electric shock.[2]]

- I have used the relevant theory: why an RCD causes a break in the circuit.[1]
- I have explicitly addressed the hazard that an RCD protects against.[2]

15 [A 9 V battery cell does not produce enough current to cause a severe shock when a human touches it[1]][because the resistance of a human in this case is far greater than the resistance of the light bulb and so the current is far lower.[2]]

- I have explicitly addressed the reason that a 9 V battery cell is safe to touch.[1]
- I have used the relevant theory: the relationship between resistance and current.[2]

Previous lessons

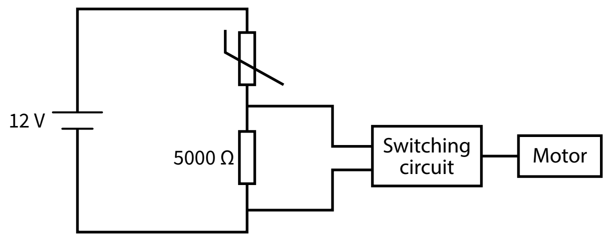
16 [It is important to use the same laboratory and take measurements at the same time of year to ensure the validity of the results.[1]][The concentration of carbon dioxide can be different in different parts of the world and it can differ throughout the year due to seasonal variations.[2]]

- I have explicitly addressed the importance of taking measurements from the same laboratory at the same time of year.[1]
- I have related my answer to the context of the question.[2]

This content was covered in Lesson 3E.

17 a 2500 Ω (1 MARK)

b



- I have used all the required components: the battery, the thermistor, one resistor, and the switching circuit.
- I have labelled the resistor with the correct resistance.
- I have connected the switching circuit in parallel across the resistor.

This content was covered in Lesson 5A.

Key science skills

18 a C (1 MARK)

The measurement uncertainty can be taken as half the range: $\frac{5.9-5.1}{2} = 0.4$ A.

b C (1 MARK)

$Avg = \frac{5.4 + 5.1 + 5.5 + 5.6 + 5.9}{5} = 5.5$ A

$Max.\ true\ value = 5.0 + 0.2 = 5.2$ A

$Min.\ error = 5.5 - 5.2 = 0.3$ A

Chapter 5 Review

Section A

1 C. $E = P \times t = 6 \times 120 \times (60 \times 60 \times 12.0) = 3.11 \times 10^7$ J

$E = \frac{3.11 \times 10^7}{3.6 \times 10^6} = 8.64$ kWh

2 D. $V_{RMS} = \frac{V_{peak}}{\sqrt{2}} \ \therefore 100 = \frac{V_{peak}}{\sqrt{2}}$

$V_{peak} = 141$ V

3 D

4 A

5 B. No current flows through the arm containing the LEDs. The current through the right arm is given by $I = \frac{V_T}{R_{eq}} = \frac{12}{200 + 400} = 0.02$ A or 20 mA.

Section B

6 **a** $E = \frac{12.50}{0.36} = 34.72$ kWh (1 MARK)

$P = \frac{E}{t} = \frac{34.72 \times 10^3 \times 60 \times 60}{3 \times 60 \times 60} = 11.573 = 12$ kW (1 MARK)

b Decrease by a factor of 4 (1 MARK)

$P = VI$, so if the power decreases by a factor of 4, then the voltage would also have to decrease by a factor of 4.

7 **a** [RCDs are ineffective against short circuits.[1]][An RCD switches off the circuit when there is a difference between the current flowing through the active and neutral wires, however a short circuit does not create such a difference.[2]]

- I have explicitly addressed whether or not the RCD is effective against short circuits.[1]
- I have used the relevant theory: RCD operation under short circuit conditions.[2]

b [Circuit breakers are effective against short circuits.[1]][A circuit breaker switches off the circuit when an excess current flows through it. In a short circuit, the path of zero resistance causes a large current, which will be detected by the circuit breaker.[2]]

- I have explicitly addressed whether or not the circuit breaker is effective against short circuits.[1]
- I have used the relevant theory: circuit breaker operation under short circuit conditions.[2]

c [Earth wires are ineffective against short circuits.[1]][The earth wire provides a pathway for leaking current to flow to the ground, however the short circuit does not create a pathway for current to leak from the device.[2]]

- I have explicitly addressed whether or not the earth pin is effective against short circuits.[1]
- I have used the relevant theory: earth wire operation under short circuit conditions.[2]

8 $V_{RMS} = \frac{V_{peak}}{\sqrt{2}} = \frac{250}{\sqrt{2}} = 176.777$ V (1 MARK)

$I_{RMS} = \frac{V_{RMS}}{R} = \frac{176.777}{1.3 \times 10^3} = 0.136$ A

$P = V_{RMS} I_{RMS} = 176.777 \times 0.136 = 24.04$ W $= 0.02404$ kW (1 MARK)

8 PM to 8 AM is 12 hours $\therefore t = 12$ h

$Cost = E \times rate = P \times t \times 0.36 = 0.02404 \times 12 \times 0.36 = 0.1034 = 0.10$

It costs $0.10 to run the Christmas lights. (1 MARK)

9 **a** From the graph, $V_{LED} = 1.5$ V (1 MARK)

In each arm, $6.0 = V_1 + 3 \times V_{LED}$

$V_1 = 1.5$ V (1 MARK)

$V_1 = I_1 R_1 \ \therefore 1.5 = I_1 \times 100$

$I_1 = 0.015$ A $= 15$ mA (1 MARK)

b On: LEDs *D*, *E* and *F* (1 MARK)

Off: LEDs *A*, *B* and *C* (1 MARK)

10 **a** [So that the switching circuit voltage increases to reach its threshold voltage as the temperature increases, the voltage drop across the thermistor should decrease with increasing temperature.[1]][Since resistance is proportional to voltage by $V = IR$,[2]][this means that B is the correct thermistor to use.[3]]

- I have referenced the required change in thermistor voltage drop as temperature increases.[1]
- I have used the relevant theory: Ohm's Law.[2]
- I have explicitly referenced thermistor **B**.[3]

b From the graph, at 10°C $R_{TH} = 2.0 \times 10^2\ \Omega$ (1 MARK)

Using the voltage divider equation,

$V_{switching\ circuit} = \frac{R_2}{R_2 + R_{TH}} \times V_T = \frac{1.2 \times 10^3}{1.2 \times 10^3 + 2.0 \times 10^2} \times 240$ V (1 MARK)

$V_{switching\ circuit} = 205.7 = 2.1 \times 10^2$ V (1 MARK)

c R_2 and switching circuit: $R_{\parallel} = \left(\frac{1}{1.2 \times 10^3} + \frac{1}{2.4 \times 10^3}\right)^{-1} = 800\ \Omega$ (1 MARK)

$R_T = R_{\parallel} + R_{TH} = 800 + R_{TH}\ \Omega$

$I_T = \frac{V_T}{R_T} \ \therefore 200 \times 10^{-3} = \frac{240}{800 + R_{TH}}$

$R_{TH} = 400 = 4.0 \times 10^2\ \Omega$ (1 MARK)

From the graph, when $R_{TH} = 4.0 \times 10^2\ \Omega$, the temperature is 6.5°C. (1 MARK)

Unit 1, AOS 2 Review

Section A

1 B. Voltage is the energy per unit charge. Suppose there are n coulombs of charge in the dome. Then $V = \frac{E}{Q} = \frac{1.2 \times 10^3 \times n}{n} = 1.2 \times 10^3$ V.

This content was covered in Lesson 4A.

2 B. $V_{RMS} = \frac{V_{peak}}{\sqrt{2}} = \frac{5.00 \times 10^2}{\sqrt{2}} = 354$ V

This content was covered in Lesson 5B.

3 D. In the series circuit, the supply voltage will be split between each LED so that the voltage drop across a single LED will be smaller than the threshold voltage. This means that in the series circuit, neither LED will light up. In the parallel circuit, both LEDs will have a voltage drop equal to their threshold voltage, so they will light up.

This content was covered in Lessons 4C, 4D and 5A.

4 D. The wiring of the multimeter changes depending on what it is being used to measure.

This content was covered in Lesson 4A.

5 C. For both ohmic and non-ohmic devices, given the values of two of the current, voltage, and resistance, we can use Ohm's Law to solve for the third value.

This content was covered in Lesson 4B.

Section B

6 **a** $P = \frac{E}{\Delta t}$, since $\Delta t = 1$ s, $E = 30.0$ J

$V = \frac{E}{Q}$ $\therefore 12.0 = \frac{30.0}{n \times q(e^-)}$ (1 MARK)

$n \times q(e^-) = 2.5$

$n \times 1.6 \times 10^{-19} = 2.5$ $\therefore n = 1.56 \times 10^{19}$ electrons (1 MARK)

This content was covered in Lesson 4A.

b $P = \frac{30.0}{3} = 10.0$ W (1 MARK)

This content was covered in Lesson 4A.

7 $V = IR$ $\therefore 200 \times 10^{-3} = 0.30 \times R$

$R = 0.667\ \Omega$ (1 MARK)

$A = \pi r^2 = \pi \times \left(\frac{6.70 \times 10^{-3}}{2}\right)^2$ (1 MARK)

$A = 3.53 \times 10^{-5}$ m^2 (1 MARK)

$R = \rho\frac{L}{A}$ $\therefore 0.667 = 7.8 \times 10^{-5} \times \frac{L}{3.53 \times 10^{-5}}$

$L = 0.30$ m (1 MARK)

This content was covered in Lesson 4B.

8 **a** 0 V (1 MARK)

There is no potential difference across the voltmeter (all of it is dropped across the open switch).

This content was covered in Lesson 4A.

b $V_T = IR_T$ $\therefore I = \frac{V_T}{R_T} = \frac{12.0}{1200 + 600} = 6.67 \times 10^{-3}$ A (1 MARK)

$V_2 = IR_2 = 6.67 \times 10^{-3} \times 600 = 4.00$ V

The voltmeter should measure a voltage of 4.00 V. (1 MARK)

OR

$V_2 = \frac{R_2}{R_1 + R_2} \times V_T$ $\therefore V_2 = \frac{600}{1200 + 1600} \times 12.0$ (1 MARK)

$V_2 = \frac{1}{3} \times 12.0 = 4.00$ V (1 MARK)

This content was covered in Lessons 4B and 4C.

c $V_{motor} = I_{motor}R_{motor}$ $\therefore I_{motor} = \frac{V_{motor}}{R_{motor}} = \frac{4.0}{170} = 2.35 \times 10^{-2}$ $= 23.5$ mA (1 MARK)

$V_1 + V_{motor} = 12.0$ $\therefore V_1 = 12.0 - 4.0 = 8.0$ V

$V_2 = 4.0$ V

$V_2 = I_2R_2$ $\therefore I_2 = \frac{V_2}{R_2} = \frac{4.0}{600} = 6.67 \times 10^{-3}$ A (1 MARK)

$I_1 = I_2 + I_{motor} = 6.67 \times 10^{-3} + 23.5 \times 10^{-3} = 30.2 \times 10^{-3}$ A

$V_1 = I_1R_1$ $\therefore R_1 = \frac{V_1}{I_1} = \frac{8.0}{30.2 \times 10^{-3}} = 264.94 = 2.6 \times 10^2\ \Omega$ (1 MARK)

This content was covered in Lessons 4B, 4C, and 4D.

9 **a** First consider the parallel circuit involving resistors B, C, D and E.

$R_{T'} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$

$\frac{1}{R_{T'}} = \frac{1}{R_B} + \frac{1}{R_C + R_D + R_E} = \frac{1}{8.00} + \frac{1}{3 \times 8.00}$

$R_{T'} = 6.00\ \Omega$ (1 MARK)

Now consider the series circuit consisting of resistor A and the parallel circuit.

$R_T = R_A + R_{T'}$ (1 MARK)

$R_T = 8.00 + 6.00 = 14.0\ \Omega$

This content was covered in Lesson 4E.

b First consider component A:

$V_T = I_AR_T$ $\therefore I_A = \frac{V_T}{R_T} = \frac{4 \times 3.0}{14.0} = 0.8571$ A (1 MARK)

$V_B = V_T - V_A = 12.0 - I_AR_A = 12.0 - 0.8571 \times 8.00$

$V_B = 5.143$ V (1 MARK)

$V_B = I_BR_B$ $\therefore I_B = \frac{V_B}{R_B} = \frac{5.143}{8.00} = 0.643$ A (1 MARK)

This content was covered in Lesson 4E.

c $R_C = R_D = R_E$ so $V_C = V_D = V_E$ (1 MARK)

Consider the loop through resistors A, C, D and E:

$V_T = V_A + V_C + V_D + V_E$ $\therefore 12.0 = 0.8571 \times 8.00 + 3 \times V_D$

$V_D = 1.714$ V (1 MARK)

$V_D = I_D R_D \therefore 1.714 = I_D \times 8.00 \therefore I_D = 0.2143$ A (or use $I_D = I_T - I_A$)

$P_D = V_D I_D = 1.714 \times 0.2143 = 0.367$ W (1 MARK)

This content was covered in Lesson 4E.

10 a Non-ohmic (1 MARK)

For an ohmic device, the gradient of the *I-V* graph (the resistance) is constant.

This content was covered in Lesson 4B.

b From the *I-V* graph, a current of 15 mA means that the voltage across the LED is 3.4 V. (1 MARK)

$V_{280\,\Omega} = I_{280\,\Omega} R_{280\,\Omega} = 15 \times 10^{-3} \times 280 = 4.2$ V (1 MARK)

$V_{battery} = V_{LED} + V_{280\,\Omega} = 3.4 + 4.2 = 7.6$ V (1 MARK)

c [The LED component converts electrical energy into light energy,[1]] [whilst the resistor converts electrical energy into thermal energy.[2]]

- I have used the relevant theory: energy conversion of an LED.[1]
- I have used the relevant theory: energy conversion of a resistor.[2]

This content was covered in Lessons 4A and 5A.

11 a [If household appliances are wired in series, one appliance being switched off or a fault in the circuit would cause all other appliances in the circuit to stop working.[1]][Furthermore, adding components in series increases the equivalent resistance of the circuit and therefore decreases the current flowing at a given supply voltage. This would mean the overall power consumption of devices is much lower, for example meaning that lightbulbs would shine more dimly than intended (or not at all).[2]]

- I have explicitly referenced what happens when a component breaks for a series circuit.[1]
- I have used the relevant theory: current and power consumption in a series circuit.[2]

This content was covered in Lessons 4A and 5B.

b [The fact that the appliances do not have an earth pin means that they are not grounded. If the uninsulated exterior of one of the appliances is in contact with the active wire, the path of least resistance for the electricity would be through the user to the ground.[1]][The current of an electric shock is what determines its severity.[2]][Since the resistance of wet skin is 100–1000 times less than that of dry skin, if a member of the family made contact with a 'live' appliance's exterior when it was wet, a high and therefore dangerous current would flow through them.[3]]

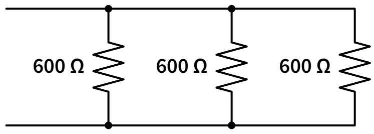
- I have used the relevant theory: earth wires.[1]
- I have used the relevant theory: effects of voltage and current on electric shocks.[2]
- I have explicitly addressed the use of the appliances in wet conditions.[3]

This content was covered in Lesson 5C.

12 a $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$

For a 200 Ω resistor, we have $\frac{1}{200} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$.

$\frac{1}{600} + \frac{1}{600} + \frac{1}{600} = \frac{3}{600} = \frac{1}{200}$ (1 MARK)



- I have drawn resistors connected in parallel or series as required.
- I have selected resistor positions that have an equivalent resistance of 200 Ω.

This content was covered in Lessons 4D and 4E.

b The equivalent resistance of the 100 Ω, 200 Ω and 300 Ω resistors is given by

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$

$\frac{1}{R_T} = \frac{1}{100} + \frac{1}{200} + \frac{1}{300} = \frac{11}{600}$

$R_T = \frac{600}{11} = 54.5\ \Omega$ (1 MARK)

[It is impossible for the circuit to have an equivalent resistance of 75 Ω.[1]][Considering the three known resistors in parallel, their equivalent resistance is $R_T = 54.5\ \Omega$.[2]][Adding an arm to a parallel circuit must decrease the equivalent resistance, so since the equivalent resistance of the three known resistors is less than 75 Ω, it is impossible for the four arms combined to have an equivalent resistance of 75 Ω, regardless of the value of the unknown resistor.[3]]

- I have explicitly addressed that the student is incorrect.[1]
- I have used calculations to support my conclusion.[2]
- I have used the relevant theory: equivalent resistance of parallel circuits.[3]

This content was covered in Lesson 4D.

13 a When *illumination* = 10 lux, $R_{LDR} = 1.0 \times 10^4\ \Omega$ (1 MARK)

$V_{out} = \frac{R_2}{R_1 + R_2} \times V_T \therefore 6 = \frac{1.0 \times 10^4}{R + 1.0 \times 10^4} \times 24$ (1 MARK)

$R = 3.0 \times 10^4$ (1 MARK)

Noting that the resistor must take up 3 times the voltage the LDR takes up and therefore will have 3 times the resistance is also acceptable.

This content was covered in Lesson 5A.

b [V_{out} will increase.[1]][The graph shows that as the illumination decreases, R_{LDR} increases.[2]][So, because $V = IR$, and I is constant, V_{out} will also increase.[3]]

- I have explicitly addressed how V_{out} changes as daylight decreases.[1]
- I have explicitly addressed how the resistance of the LDR changes as daylight decreases.[2]
- I have used the relevant theory: Ohm's Law.[3]

This content was covered in Lesson 5A.

c [Increase.[1]][This change means more of the voltage will drop across the resistor, and less across the LDR,[2]][so the LDR will require a higher resistance and hence a lower light level for the same value of V_{out}.[3]]

- I have explicitly addressed whether Randall should increase or decrease the resistance of R.[1]
- I have explicitly addressed how a change in the resistor's resistance will affect the voltage across the switching circuit.[2]
- I have referred to the fact that the LDR requires a lower light level for a higher resistance.[3]

This content was covered in Lessons 4C and 5A.

6A The Standard Model

Theory review questions

1 W-Nucleus; X-Neutron; Y-Proton; Z-Electron

2

		Elementary	Composite
a	Electron	✓	
b	Proton		✓
c	Up quark	✓	
d	Pion		✓
e	Higgs boson	✓	
f	Tau neutrino	✓	
g	Strange antiquark	✓	
h	Hydrogen atom		✓
i	Photon	✓	
j	Positron	✓	

3 **a** Up quark (quark)
b Tau particle (lepton)
c Muon neutrino (lepton)
d Bottom antiquark (quark)
e Z boson (boson)
f Electron (lepton)
g Positron (lepton)
h Charm quark (quark)
i Muon (lepton)
j Photon (boson)

4 **a** False
b True
c True
d False

Deconstructed exam-style question

5 **a** D

b B

c D

d Before the decay: 1

After the decay: 1 + 0 + 0 = 1

They are the same.

e Before the decay: 0

After the decay: 0 + 1 − 1 = 0

They are the same.

f conservation of baryon number; (1 MARK)

conservation of lepton number; (1 MARK)

Plus two of the following: conservation of charge; conservation of momentum; conservation of angular momentum; conservation of energy (2 MARKS)

Exam-style questions

This lesson

6 [Anderson had cosmic rays pass through a cloud chamber under an external magnetic field.[1]][He observed a particle that had the same mass-to-charge ratio as an electron, but which bent in a direction that indicated it had a positive charge. It was this particle he called the positron.[2]]

- I have explicitly addressed Anderson's experimental method.[1]
- I have used the relevant theory: evidence for the positron.[2]

7 [The Standard Model divides elementary particles into three main categories: quarks, leptons and bosons.[1]][There are six quarks in three generations (up, down, strange, charm, top and bottom).[2]][Leptons encompass three generations of particles and their corresponding neutrinos: electron, muon and tau.[3]][Bosons include the four gauge bosons responsible for fundamental forces and the Higgs boson.[4]]

- I have explicitly addressed the three categories of elementary particles.[1]
- I have used the relevant theory: members of the quarks.[2]
- I have used the relevant theory: members of the leptons.[3]
- I have used the relevant theory: members of the bosons.[4]

8 **a** $\bar{u}\,\bar{u}\,\bar{d}$ (1 MARK)

b Charge $= -\frac{1}{3} - \frac{1}{3} - \frac{1}{3} = -1$ as expected (1 MARK)

9 **a** $B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$ (1 MARK)

baryon (1 MARK)

b $B = \frac{1}{3} - \frac{1}{3} = 0$ (1 MARK)

meson (1 MARK)

c $B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} - \frac{1}{3} = 1$ (1 MARK)

baryon (1 MARK)

d $B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$ (1 MARK)

baryon (1 MARK)

10 **a** $S = -1 - 1 - 1 = -3$ (1 MARK)

b $S = 0 + 1 = 1$ (1 MARK)

c $S = 0 + 0 + 0 + 0 + 0 = 0$ (1 MARK)

d $S = 0 - 1 - 1 = -2$ (1 MARK)

11 [Baryons are composed of an odd number of quarks (generally 3),[1]][whereas a meson is composed of one quark and one antiquark.[2]]

- I have used the relevant theory: baryon composition.[1]
- I have used the relevant theory: meson composition.[2]

12 **a** [The neutron is not its own antiparticle.[1]][While the neutron has no charge, it has a baryon number of +1. The antineutron has a baryon number of −1.[2]]

- I have explicitly addressed whether the neutron is its own antiparticle.[1]
- I have used the relevant theory: baryon number.[2]

b [The neutral pion is its own antiparticle.[1]][The quark composition of the antiparticle is (ūu), which is the same as the composition of the neutral pion.[2]]

- I have explicitly addressed whether the neutron is its own antiparticle.[1]
- I have used the relevant theory: antiparticle composition.[2]

OR

[The neutral pion is its own antiparticle.[1]][All of its relevant quantum numbers that are equal and opposite for its antiparticle are zero. [2]]

- I have explicitly addressed whether the neutron is its own antiparticle.[1]
- I have used the relevant theory: antiparticle composition.[2]

Previous lessons

13 [There is a positive feedback between temperature and the amount of greenhouse gases in the atmosphere.[1]][Increasing the Earth's albedo would decrease the temperature of the Earth,[2]][which would result in a decrease in greenhouse gas concentrations and so reduce the greenhouse effect.[3]]

- I have used the relevant theory: feedback between temperature and greenhouse gases.[1]
- I have used the relevant theory: effect of albedo.[2]
- I have related my answer to the context of the question.[3]

This content was covered in Lesson 3E.

14 From the graph: $V_P = 325$ V (1 MARK)

$$V_{RMS} = \frac{V_P}{\sqrt{2}} = \frac{325}{\sqrt{2}} = 230 \text{ V}$$ (1 MARK)

This content was covered in Lesson 5B.

Key science skills

15 **a** Formulate a hypothesis (1 MARK)

b [Performing a series of experiments that produce the same result is a good indicator that the results are reliable.[1]][The repeatability of the experiments (getting results that agree across several repetitions) also indicates that the results are reliable.[2]]

- I have used the relevant theory: reliability.[1]
- I have used the relevant theory: repeatability.[2]

6B Nuclear stability and the fundamental forces

Theory review questions

1 repulsive; attractive; nucleons; quarks

2 **a** X **b** Z **c** A

3

	Acts on protons	Acts on neutrons	Acts at long distances	Acts at short distances
Strong force	✓	✓		✓
Weak force	✓	✓		✓
Electromagnetic force	✓		✓	✓

4 **a** N (number of neutrons)

b Z (number of protons)

c Valley of Stability

d $N = Z$ line

5 D

6 A and D

Deconstructed exam-style question

7 **a** A

b C

c [This isotope of neon will be stable[1]][as it has $Z = 10$ and $N = 10$[2]][which means it follows the $N = Z$ stability rule for $Z \leq 20$).[3]]

- I have explicitly addressed whether the isotope is stable or unstable.[1]
- I have used the relevant theory: nuclear notation.[2]
- I have used the relevant theory: nuclear stability.[3]

Exam-style questions

This lesson

8 **a** $Z = 16, N = 16, A = 32$

$Z \leq 20$, therefore use $N = Z$ (1 MARK)

Stable (1 MARK)

b $Z = 84, N = 124, A = 208$

$Z \geq 84$ (1 MARK)

Unstable (1 MARK)

c $Z = 82, N = 126, A = 208$

Check valley of stability diagram.
(Note: likely to be stable as more neutrons than protons) (1 MARK)

Stable (1 MARK)

d $Z = 35, N = 35, A = 70$

Check valley of stability diagram **OR** Note $N = Z$ but $Z > 20$ (1 MARK)

Unstable (1 MARK)

9 a $Z = 15, N = 15$

$Z \leq 20$, therefore use $N = Z$ (1 MARK)

Stable (1 MARK)

b $N = 45, Z = 45$

Check valley of stability diagram **OR** Note $N = Z$ but $Z > 20$ (1 MARK)

Unstable (1 MARK)

c $Z = 87, A = 223$

$Z \geq 84$, therefore inherently unstable (1 MARK)

Unstable (1 MARK)

d $A = 85, N = 48, Z = 37$

Check valley of stability diagram.
(Note: likely to be stable as more neutrons than protons) (1 MARK)

Stable (1 MARK)

10 [An isotope is an atom of an element that has a different number of neutrons (but the same number of protons) compared to another atom of the element.[1]][A radioisotope is the kind of isotope that will undergo radioactive decay.[2]]

- I have used the relevant theory: isotopes.[1]
- I have used the relevant theory: radioisotopes.[2]

11 [A nucleus with too many protons will experience a greater repulsive electrostatic force between the protons[1]][than the attractive strong force between the nucleons (protons and neutrons).[2]][This makes the nucleus unstable.[3]]

- I have used the relevant theory: electrostatic force in the nucleus.[1]
- I have used the relevant theory: strong force in the nucleus.[2]
- I have explicitly addressed the instability of the nucleus.[3]

12 [Genevieve is correct.[1]][Jana claims that the nucleus is stable if $N = Z$. However, this only true for elements with $Z \leq 20$, so she is incorrect.[2]] [As $Z = 79$ for gold ($Z > 20$), Genevieve is correct that this stability rule does not apply.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: nuclear stability for $Z \leq 20$.[2]
- I have used the relevant theory: nuclear stability for $Z > 20$.[3]

Previous lessons

13 [Double glazed windows consist of two pieces of glass with air trapped between them.[1]][As air is a poor conductor of heat,[2]][much less heat can transfer through the window.[3]]

- I have explicitly addressed the construction of a double glazed window.[1]
- I have explicitly addressed that air is a poor conductor.[2]
- I have referenced the reduced ability to transfer heat.[3]

This content was covered in Lesson 3F.

14 Two of: duration of shock, the size of the current through the person, the person's resistance, the current's path through the body (e.g. through the heart)

This content was covered in Lesson 5C.

Key science skills

15 a Independent variable

b Dependent variable

c [The identity of an element is determined by its Z value.[1]][This allows the independent axis to identify the elements, and the vertical axis to then identify the stability of its corresponding isotopes.[2]]

- I have used the relevant theory: nuclear notation.[1]
- I have used the relevant theory: relationship between horizontal and vertical axes.[2]

6C Radioactive half-life

Theory review questions

1 C. Two hours corresponds to two half-lives. After one half-life, 50% remains. After two half-lives, 50% of that amount (i.e. 25% of the original amount) still remains.

2 B. After two half-lives, 25% of the original amount remains. 25% of 10 grams is 2.5 grams.

3 A. Half-life is entirely determined by the radioisotope.

4 A, B, C. Activity depends on the radioisotope (because some substances are more unstable than others), the amount of the substance remaining (because a fixed proportion of the available nuclei will decay in a given time, so more nuclei means more decays), and it changes as time passes (because the amount of the substance that remains decreases as time passes).

Deconstructed exam-style question

5 a A. $\frac{6}{24} = 0.25$

b B. $\frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^2 = 0.25 \;\therefore n = 2$

c C. $t_{1/2} = \frac{T}{n} = \frac{28\text{ days}}{2\text{ half-lives}} = 14\text{ days}$

d Use the known data to calculate the half-life.

$m = m_0\left(\frac{1}{2}\right)^n \quad \therefore 6 = 24 \times \left(\frac{1}{2}\right)^n$

$n = 2$ half-lives until only 6 mg remains. (1 MARK)

$t_{1/2} = \frac{T}{n} = \frac{28 \text{ days}}{2 \text{ half-lives}} = 14 \text{ days}$ (1 MARK)

Use the half-life to calculate the time required.

$m = m_0\left(\frac{1}{2}\right)^n \quad \therefore 1.5 = 24 \times \left(\frac{1}{2}\right)^n$

$\left(\frac{1}{2}\right)^n = \frac{1.5}{24} = 0.0625 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^4$

(or use $n = \frac{\log(0.0625)}{\log(1/2)} = 4$)

$n = 4$ half-lives until only 1.5 mg remains. (1 MARK)

$T = n \times t_{1/2} = 4 \times 14 \text{ days} = 56 \text{ days}$ (1 MARK)

Exam-style questions

This lesson

6 a $m = m_0 \times \left(\frac{1}{2}\right)^n = 0.840 \times \left(\frac{1}{2}\right)^3 = 0.105 \text{ g}$ (1 MARK)

b The amount that remains is:

$m = m_0 \times \left(\frac{1}{2}\right)^n = 0.840 \times \left(\frac{1}{2}\right)^4 = 0.0525 \text{ g}$ (1 MARK)

The amount that has decayed is:

$m_0 - m = 0.840 - 0.0525 = 0.7875 = 0.79 \text{ g}$ (1 MARK)

7 a 8 weeks = 8 × 7 days = 56 days

$n = \frac{T}{t_{1/2}} = \frac{56}{8.0} = 7$ half-lives (1 MARK)

$N = N_0\left(\frac{1}{2}\right)^n = 5.0 \times 10^{10} \times \left(\frac{1}{2}\right)^7 = 3.9 \times 10^8$ atoms (1 MARK)

b $N = N_0\left(\frac{1}{2}\right)^n \quad \therefore 6.25 \times 10^9 = 5.0 \times 10^{10} \times \left(\frac{1}{2}\right)^n$

$\left(\frac{1}{2}\right)^n = \frac{6.25 \times 10^9}{5.0 \times 10^{10}} = 0.125 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^3$

(or use $n = \frac{\log(0.125)}{\log(1/2)} = 3$)

$n = 3$ half-lives until only 6.25×10^9 atoms remain. (1 MARK)

$T = n \times t_{1/2} = 3 \times 8.0 \text{ days} = 24 \text{ days}$ (1 MARK)

8 a $t_{1/2} = 200$ seconds (1 MARK)

b 20 minutes = 20 × 60 s = 1200 s

$n = \frac{T}{t_{1/2}} = \frac{1200}{200} = 6$ half-lives (1 MARK)

$A = A_0\left(\frac{1}{2}\right)^n = 160 \times 10^3 \times \left(\frac{1}{2}\right)^6 = 2.50 \times 10^3 \text{ Bq}$ (1 MARK)

c $n = \frac{T}{t_{1/2}} = \frac{400}{200} = 2$ half-lives (1 MARK)

$m = m_0\left(\frac{1}{2}\right)^n = 40 \times \left(\frac{1}{2}\right)^2 = 10 \text{ g}$ (1 MARK)

9 $n = \frac{T}{t_{1/2}} = \frac{90}{15} = 6$ half-lives (1 MARK)

$A = A_0\left(\frac{1}{2}\right)^n \quad \therefore 5000 = A_0\left(\frac{1}{2}\right)^6$ (1 MARK)

$A_0 = 3.2 \times 10^5 \text{ Bq}$ (1 MARK)

10 Use the known data to calculate the half-life.

$m = m_0\left(\frac{1}{2}\right)^n \quad \therefore 12.5 = 50 \times \left(\frac{1}{2}\right)^n$

$n = 2$ half-lives until only 12.5 mg remains. (1 MARK)

$t_{1/2} = \frac{T}{n} = \frac{10.6 \text{ years}}{2 \text{ half-lives}} = 5.3 \text{ years}$ (1 MARK)

Use the half-life to calculate the time required.

$m = m_0\left(\frac{1}{2}\right)^n \quad \therefore 6.25 = 50 \times \left(\frac{1}{2}\right)^n$

$\left(\frac{1}{2}\right)^n = \frac{6.25}{50} = 0.125 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^3$

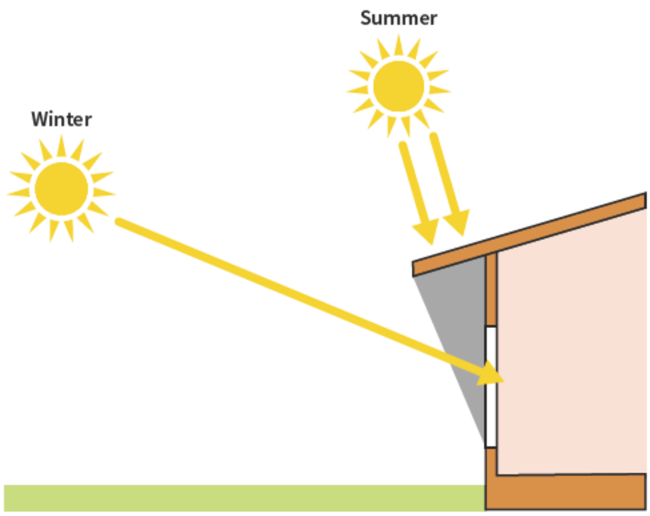
(or use $n = \frac{\log(0.125)}{\log(1/2)} = 3$)

$n = 3$ half-lives until only 6.25 mg remains. (1 MARK)

$T = n \times t_{1/2} = 3 \times 5.3 \text{ years} = 15.9 \text{ years}$ (1 MARK)

Previous lessons

11 [Eaves provide shade from the Sun when it is high in the sky, which helps keep the house cool during summer[1]][but they do not provide shade during winter when the Sun is lower in the sky, so the sunlight can warm the house when it is cold.[2]]



- I have used the relevant theory: eaves provide shade in summer.[1]
- I have used the relevant theory: eaves do not provide shade in winter.[2]
- I have drawn a diagram that shows sunlight from a summer Sun being blocked by the eave.
- I have drawn a diagram that shows sunlight from a winter Sun entering the window.

This content was covered in Lesson 3F.

6C

12 [Both devices are used for safety reasons.[1]][A fuse interrupts the flow of electricity to prevent fires and damage to appliances whereas RCDs interrupt the flow of electricity to prevent electrical shock.[2]]

- I have explicitly addressed a similarity between the two devices.[1]
- I have explicitly addressed a difference between the two devices.[2]

This content was covered in Lesson 5C.

Key science skills

13 a Choose two points from the graph that are well separated to calculate gradient.

$gradient = \frac{rise}{run} = \frac{4-9}{300-0}$ (1 MARK)

$gradient = -0.0167$ (1 MARK)

b Given the equation $\ln(A) = -\frac{0.693}{t_{1/2}} \times t + 9$ (which can be compared with $y = mx + c$), the gradient must be $-\frac{0.693}{t_{1/2}}$.

$-\frac{0.693}{t_{1/2}} = -0.0167$ (1 MARK)

$t_{1/2} = 41.58 = 42$ days (1 MARK)

6D Types of nuclear radiation

Theory review questions

1 a charge: +2, mass number: 4

b charge: +1, mass number: 0

c charge: −1, mass number: 0

d charge: 0, mass number: 0

2 a Gamma decay

b Beta plus decay

c Alpha decay

d Beta minus decay

3 B

4 A

5 a Alpha decay

b Beta plus decay

c Beta minus decay

d Gamma decay

Deconstructed exam-style question

6 a B **b** C **c** C

d Parent nuclide: $Z = 90$, $A = 232$

6 alpha decays: Z decreases by $6 \times 2 = 12$, A decreases by $6 \times 4 = 24$. (1 MARK)

4 beta minus decays: Z increases by $4 \times 1 = 4$, A does not change. (1 MARK)

Therefore, daughter nuclide: $Z = 90 - 12 + 4 = 82$, $A = 232 - 24 + 0 = 208$

Daughter nuclide is $^{208}_{82}Pb$ (1 MARK)

Exam-style questions

This lesson

7 [Penetrating power refers to the ability of a given type of radiation to travel through matter before it loses its energy[1]][Radiation loses its energy through ionising other atoms,[2]][therefore the more ionising a given type of radiation is, the less penetrating it is.[3]]

- I have used the relevant theory: penetrating power.[1]
- I have used the relevant theory: ionisation.[2]
- I have explicitly addressed the relationship between ionising power and penetrating power.[3]

8 a $^{0}_{-1}e + ^{0}_{0}\bar{v}$ (1 MARK)

b $^{4}_{2}He$ (1 MARK)

c $^{0}_{0}\gamma$ (1 MARK)

d $^{0}_{+1}e + ^{0}_{0}v$ (1 MARK)

9 a The alpha particle has a charge of +2 and a mass number of 4.

Daughter nuclide proton number = $Z - 2 = 78 - 2 = 76$ (∴ chemical symbol is Os)

Daughter nuclide mass number = $A - 4 = 175 - 4 = 171$.

$^{171}_{76}Os$ (2 MARKS)

b The beta minus particle and antineutrino together have a total charge of −1 and a total mass number of 0.

Daughter nuclide proton number = $Z + 1 = 88 + 1 = 89$ (∴ chemical symbol is Ac)

Daughter nuclide mass number = $A - 0 = 228 - 0 = 228$.

$^{228}_{89}Ac$ (2 MARKS)

c The beta plus particle and neutrino together have a total charge of +1 and a total mass number of 0.

Daughter nuclide proton number = $Z - 1 = 12 - 1 = 11$ (∴ chemical symbol is Na)

Daughter nuclide mass number = $A - 0 = 23 - 0 = 23$.

$^{23}_{11}Na$ (2 MARKS)

d The gamma photon has a total charge of 0 and a total mass number of 0.

Daughter nuclide proton number = $Z - 0 = 53 - 0 = 53$ (∴ chemical symbol is I)

Daughter nuclide mass number = $A - 0 = 125 - 0 = 125$.

$^{125}_{53}I$ (2 MARKS)

10 a Parent nuclide proton number = $10 + 0 = 10$ (∴ chemical symbol is Ne)

Parent nuclide mass number = $22 + 0 = 22$.

$^{22}_{10}Ne$ (2 MARKS)

b Parent nuclide proton number = 28 − 1 + 0 = 27
(∴ chemical symbol is Co)

Parent nuclide mass number = 60 + 0 + 0 = 60.

$^{60}_{27}\text{Co}$ (2 MARKS)

c Parent nuclide proton number = 91 + 2 = 93 (∴ chemical symbol is Np)

Parent nuclide mass number = 233 + 4 = 237.

$^{237}_{93}\text{Np}$ (2 MARKS)

d Parent nuclide proton number = 35 + 1 + 0 = 36
(∴ chemical symbol is Kr)

Parent nuclide mass number = 74 + 0 + 0 = 74.

$^{74}_{36}\text{Kr}$ (2 MARKS)

11 **a** Alpha decay produces a daughter nuclide and an alpha particle.

Daughter nuclide proton number = Z − 2 = 85 − 2 = 83
(∴ chemical symbol is Bi)

Daughter nuclide mass number = A − 4 = 215 − 4 = 211.

$^{215}_{85}\text{At} \rightarrow {}^{211}_{83}\text{Bi} + {}^{4}_{2}\text{He}$ (2 MARKS)

b Beta plus decay produces a positron and a neutrino.

Daughter nuclide proton number = Z − 1 = 29 − 1 = 28
(∴ chemical symbol is Ni)

Daughter nuclide mass number = A − 0 = 64 − 0 = 64.

$^{64}_{29}\text{Cu} \rightarrow {}^{64}_{28}\text{Ni} + {}^{0}_{+1}\text{e} + {}^{0}_{0}\nu$ (2 MARKS)

c Beta minus decay produces an electron and an antineutrino.

Daughter nuclide proton number = Z + 1 = 87 + 1 = 88
(∴ chemical symbol is Ra)

Daughter nuclide mass number = A − 0 = 223 − 0 = 223.

$^{223}_{87}\text{Fr} \rightarrow {}^{223}_{88}\text{Ra} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\bar{\nu}$ (2 MARKS)

d Gamma decay produces a gamma photon.

Daughter nuclide proton number = Z − 0 = 34 − 0 = 34
(∴ chemical symbol is Se)

Daughter nuclide mass number = A − 0 = 72 − 0 = 72.

$^{72}_{34}\text{Se} \rightarrow {}^{72}_{34}\text{Se} + {}^{0}_{0}\gamma$ (2 MARKS)

12 **a** Parent nuclide: Z = 237, A = 93

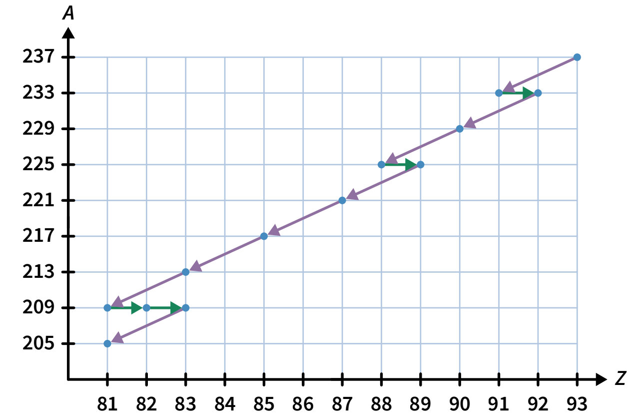
8 alpha decays: Z decreases by 8 × 2 = 16, A decreases by 8 × 4 = 32 (1 MARK)

4 beta minus decays: Z increases by 4 × 1 = 4, A does not change (1 MARK)

Therefore, daughter nuclide: Z = 93 − 16 + 4 = 81,
A = 237 − 32 + 0 = 205

Daughter nuclide is $^{205}_{81}\text{Tl}$ (1 MARK)

b



- I have shown the initial parent nuclide as $^{237}_{93}\text{Np}$ and the final daughter nuclide as $^{205}_{81}\text{Tl}$.
- I have drawn the correct sequence of alpha and beta decays.
- I have drawn alpha decays as arrows pointing down 4 units and left 2 units.
- I have drawn beta minus decays as arrows pointing right 1 unit.
- I have correctly labelled the horizontal and vertical axes and have drawn the axes with consistent spacing.

13 Beam A – Alpha radiation (1 MARK)

Beam B – Beta radiation (beta plus or beta minus) (1 MARK)

Beam C – Gamma radiation (1 MARK)

14 [Alpha decay would be represented by an arrow pointing down two units and left two units.[1]][Beta minus decay would be represented by an arrow pointing down one unit and right one unit.[2]][Beta plus decay would be represented by an arrow pointing up one unit and left one unit.[3]]

- I have used the relevant theory: alpha decay.[1]
- I have used the relevant theory: beta minus decay.[2]
- I have used the relevant theory: beta plus decay.[3]

Previous lessons

15 **a** $E = 432 \times 10^3$ J and $t = 10 \times 60 \times 60 = 3.6 \times 10^4$ s (1 MARK)

$P = \frac{E}{t} = \frac{432 \times 10^3}{3.6 \times 10^4} = 12$ W (1 MARK)

b $P = IV$ ∴ $12 = 2.0 \times V$ (1 MARK)

$V = 6.0$ V (1 MARK)

This content was covered in Lesson 4A.

16 [A positron is a type of antimatter that has the same mass and spin, but opposite charge (and other quantum numbers) to an electron.[1]] [If an electron and a positron interacted they would annihilate each other.[2]][This would release energy in the form of electromagnetic radiation or other particles.[3]]

- I have explicitly addressed the definition of the positron.[1]
- I have used the relevant theory: antimatter annihilation.[2]
- I have explicitly addressed the products of annihilation.[3]

This content was covered in Lesson 6A.

Key science skills

17 **a** 6 significant figures (1 MARK)

b 5.00 MeV = 5.00×10^6 eV (1 MARK)

$= 5.00 \times 10^6 \text{ eV} \times 1.602 \times 10^{-19} \text{ J eV}^{-1}$

$= 8.01 \times 10^{-13}$ J (1 MARK)

c $KE = \frac{1}{2}mv^2 \therefore 8.01 \times 10^{-13} = \frac{1}{2} \times 6.64466 \times 10^{-27} \times v^2$ (1 MARK)

$v = \sqrt{\frac{8.01 \times 10^{-13}}{\frac{1}{2} \times 6.64466 \times 10^{-27}}}$ (1 MARK)

$v = 1.55 \times 10^7 \text{ m s}^{-1}$ (3 significant figures) (1 MARK)

Chapter 6 review

Section A

1 D

2 A. The strong force acts over very short distances.

3 D. A neutron turns into a proton, so the sum of protons and neutrons (mass number) stays the same and the number of protons increases by 1.

4 B. Each β^- emission corresponds to an increase in the atomic number by 1 (and no change in the mass number) and the α emission corresponds to a decrease in the atomic number by 2 and a decrease in the mass number by 4.

5 D. After one half-life, that activity halves to 50% of its original value. After a second half-life, that activity halves again to 25% of its original value, which is a decrease of 75%.

Section B

6 **a** Mass is 3.17×10^{-27} kg. (1 MARK)

Charge is $+e$. (1 MARK)

b They will annihilate each other to create radiation. (1 MARK)

7 [Mesons consist of a quark and an antiquark[1]][whereas baryons consist of an odd number of quarks.[2]][They are each bound together by the strong force.[3]]

- I have explicitly addressed the composition of mesons.[1]
- I have explicitly addressed the composition of baryons.[2]
- I have explicitly addressed the force that binds mesons together and baryons together.[3]

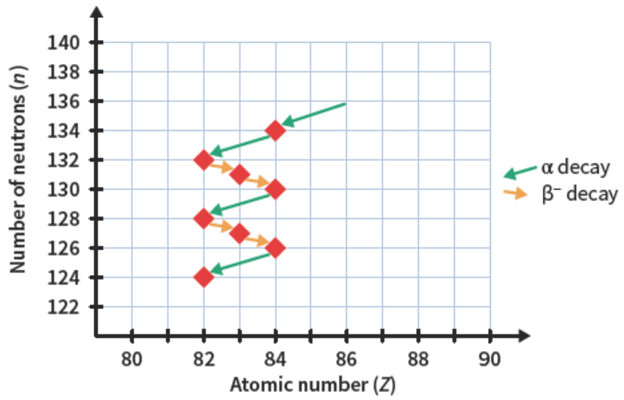
8 [A nucleus is stable if the strong force binding the nucleons (protons and neutrons) is greater than the electrostatic repulsion between the protons.[1]][Large nuclei tend to be less stable than small nuclei because the strong force acts over much shorter distances than the electrostatic force,[2]][which means that the electrostatic repulsion is the dominant force between nucleons in large nuclei whereas the strong force is the dominant force in small nuclei.[3]]

- I have explicitly addressed what makes a nucleus stable.[1]
- I have used the relevant theory: the ranges of the strong force and the electrostatic force.[2]
- I have explicitly addressed the reason that large nuclei are less stable than small nuclei.[3]

9 [A nucleus becomes smaller when it emits alpha (α) radiation.[1]][It loses two protons and two neutrons in the process.[2]]

- I have explicitly addressed which form of radiation makes the nucleus smaller.[1]
- I have explicitly addressed the changes to the nucleus that occur.[2]

10



- I have represented each alpha decay with an arrow that indicates a decrease by 2 along both the horizontal and vertical axes.
- I have represented each β^- with an arrow that indicates an increase by 1 along the horizontal axis and a decrease by 1 along the vertical axis.
- I have started the decay series from a horizontal value of 86 and a vertical value of 136.
- I have shown the decays in the correct order.

11 **a** The atomic number has decreased by 1, so β^+ decay must have occurred.

$^{40}_{19}\text{K} \rightarrow ^{40}_{18}\text{Ar} + \beta^+ + \nu$

- I have included the correct mass number for K.
- I have completed the equation with $\beta^+ + \nu$ or $^{0}_{+1}\text{e} + \nu$.

b The atomic number has decreased by 2, so α decay must have occurred.

$^{218}_{85}\text{At} \rightarrow {}^{214}_{83}\text{Bi} + \alpha$

I have included the correct mass number for Bi.

I have completed the equation with α or $^{4}_{2}\text{He}$.

12 $m = m_0\left(\frac{1}{2}\right)^n \therefore 5 = 20 \times \left(\frac{1}{2}\right)^n$

$\left(\frac{1}{2}\right)^n = \frac{5}{20} = 0.25 = \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^2$

(or use $n = \frac{\log(0.25)}{\log(1/2)} = 2$)

$n = 2$ half-lives (1 MARK)

$t_{1/2} = \frac{T}{n} = \frac{6 \text{ hours}}{2 \text{ half-lives}} = 3$ hours (1 MARK)

13 Use the known data to calculate the half-life.

$A = A_0\left(\frac{1}{2}\right)^n \therefore 200 = 1600 \times \left(\frac{1}{2}\right)^n$

$\left(\frac{1}{2}\right)^n = \frac{200}{1600} = 0.125 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^3$

(or use $n = \frac{\log(0.125)}{\log(1/2)} = 3$)

$n = 3$ half-lives until the activity is 200 Bq. (1 MARK)

$t_{1/2} = \frac{T}{n} = \frac{6 \text{ hours}}{3 \text{ half-lives}} = 2$ hours (1 MARK)

Use the half-life to calculate the number of half-lives that have passed at 10 pm.

$n = \frac{T}{t_{1/2}} = \frac{10 \text{ hours}}{2 \text{ hours}} = 5$ half-lives (1 MARK)

$A = A_0\left(\frac{1}{2}\right)^n \therefore A = 1600 \times \left(\frac{1}{2}\right)^5 = 50$ Bq (1 MARK)

7A Nuclear energy

Theory review questions

1 **a** Both **b** Nuclear fusion **c** Both
d Nuclear fission **e** Both **f** Nuclear fusion
g Both **h** Nuclear fission

2 C. Equating the mass numbers on each side gives $x = 3$.

3 A. The nucleus must be lighter than iron to release energy due to fusion and the steeper the curve, the more energy released.

4 D. The nucleus must be heavier than iron to release energy due to fission.

5 C. The most stable nucleus is highest on the binding energy curve.

6 fusion; larger; intense; release; fission; release

7 A

Deconstructed exam-style question

8 **a** C. Read the binding energy for carbon-12, 12.3×10^{-13}, and multiply by the number of nucleons, 12.

b B. A proton is an unbound nucleon and so will have zero binding energy.

c D. Read the binding energy for nitrogen-13, 11.6×10^{-13}, and multiply by the number of nucleons, 13.

$E_i = E_{carbon-13} + E_{proton} = 12.3 \times 10^{-13} \times 12 + 0 = 1.48 \times 10^{-11}$ J (1 MARK)

$E_f = E_{nitrogen-13} = 11.6 \times 10^{-13} \times 13 = 1.51 \times 10^{-11}$ J (1 MARK)

$\Delta E = E_f - E_i = 1.51 \times 10^{-11} - 1.48 \times 10^{-11} = 3.2 \times 10^{-13}$ J (1 MARK)

This reaction will release 3.2×10^{-13} J of energy.

Exam-style questions

This lesson

9 $\Delta E = \Delta mc^2$

$\Delta E = 2.202 \times 10^{-28} \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta E = 1.98 \times 10^{-11} = 2.0 \times 10^{-11}$ J (1 MARK)

10 $\Delta E = \Delta mc^2$

$2.06 \times 10^{-13} = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 2.29 \times 10^{-30} = 2.3 \times 10^{-30}$ kg (1 MARK)

11 **a** The product will have greater binding energy than the reactants.

b The products will have greater binding energy than the reactant.

12 $\Delta E = \Delta mc^2$

$2.6 \times 10^5 \times 10^9 = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 2.89 \times 10^{-3}$ kg (1 MARK)

$\frac{\Delta m}{m} \times 100\% = \frac{2.89 \times 10^{-3}}{3.6} \times 100\% = 0.080\%$ (1 MARK)

0.080% of the uranium-235 is converted to energy.

13 **a** $X_{protons} + 0 = 58 + 36 + 4 \times 0$

$X_{protons} = 94$ (1 MARK)

$X_{nucleons} + 1 = 145 + 91 + 4 \times 1$

$X_{nucleons} = 239$ (1 MARK)

$X_{neutrons} = X_{nucleons} - X_{protons} = 239 - 94 = 145$ (1 MARK)

X has 94 protons and 145 neutrons.

b $\Delta E = \Delta mc^2$

$1.0 \times 10^{12} = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 1.1 \times 10^{-5}$ kg (1 MARK)

$\frac{1.1 \times 10^{-5}}{m} \times 100 = 0.10$ (1 MARK)

$m = 0.011 = 1.1 \times 10^{-2}$ kg of reactant X is required. (1 MARK)

14 *binding energy = number of nucleons × binding energy per nucleon*

binding energy = $56 \times 1.41 \times 10^{-12} = 7.88 \times 10^{-11}$ J (1 MARK)

The total binding energy is related to the mass defect by $\Delta E = \Delta mc^2$.

$\Delta E = \Delta mc^2$

$7.88 \times 10^{-11} = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 8.76 \times 10^{-28}$ kg (1 MARK)

Iron-56 has a mass defect of 8.76×10^{-28} kg.

15 **a** [The gradient of the binding energy curve is steeper in the region that will undergo fusion compared to the region that will undergo fission.[1]] [Hence we would expect a fusion reaction to release more energy per nucleon.[2]]

- I have justified my answer with the relevant theory: features of the binding energy curve.[1]
- I have explicitly addressed which reaction will release more energy per nucleon.[2]

b [In a typical fission reaction, the number of nucleons is far greater than in a typical fusion reaction.[1]] [This difference is by a greater factor than the difference in energy released per nucleon.[2]] [Hence a fission reaction will release more energy than a fusion reaction.[3]]

- I have justified my answer with the relevant theory: reactants of nuclear reactions.[1]
- I have justified my answer with the relevant theory: features of the binding energy curve.[2]
- I have explicitly addressed which reaction will release more energy.[3]

16 [The energy released in the reaction depends on the difference in binding energies between the reactant and the products.[1]][In both processes the reactant is the same and the products are the same and hence have the same binding energies,[2]][so we would expect the reaction to release the same amount of energy, irrespective of the pathway.[3]] [Hence the proton-proton reaction will release the same energy as the CNO reaction.[4]]

- I have justified my answer with the relevant theory: Binding energy in reactions.[1]
- I have referenced how both pathways have the same reactant and products.[2]
- I have referenced how the difference in binding energy determines the energy release.[3]
- I have explicitly addressed the difference in energy between the two pathways.[4]

Previous lessons

17 $P = VI$

$500 = 120 \times I$ (1 MARK)

$I = 4.17$ A

$Q = It$

$Q = 4.17 \times 10 \times 60$ (1 MARK)

$Q = 2500 = 2.5 \times 10^3$ C (1 MARK)

OR

$E = Pt = 500 \times 10 \times 60$

$E = 3.0 \times 10^5$ J (1 MARK)

$Q = \frac{E}{V} = \frac{3.0 \times 10^5}{120}$ (1 MARK)

$Q = 2500 = 2.5 \times 10^3$ C (1 MARK)

This content was covered in Lesson 4A.

18 [This isotope of iron will be unstable[1]][as it has $Z = 26$ (> 20) but also has $N = Z$ ($N = 52 - 26 = 26$).[2]][Only elements with $Z \leq 20$ follow the $N = Z$ stability rule. An iron isotope should have more neutrons than protons to be stable.[3]]

- I have explicitly addressed if the isotope is stable or unstable.[1]
- I have used the relevant theory: nuclear notation.[2]
- I have used the relevant theory: nuclear stability.[3]

This content was covered in Lesson 6B.

Key science skills

19 [It would not be appropriate to fit a line of best fit.[1]][The data points show that there is not a linear trend, rather there is an obvious curve and so the students should not plot a line of best fit.[2]]

- I have explicitly addressed whether a line of best fit is appropriate.[1]
- I have justified my answer with the relevant theory: lines of best fit.[2]

7B Producing light

Theory review questions

1 acceleration; changing; changing

2 A. X, it touches the circle exactly once (and is perpendicular to the radius of the circle).

3 A. X represents the tangent. This is the direction that electromagnetic radiation emitted at that point would travel.

4 B. Particle T is changing direction and therefore accelerating. This results in the release of electromagnetic radiation.

5 D. Both particles S and T are accelerating (deceleration is a type of acceleration). This results in the release of electromagnetic radiation.

6 A. The words ‘light’ and ‘radiation’ are used interchangeably to refer to electromagnetic radiation.

7 a continuous spectrum of; discrete

8 B. M and Q move between the same two energy levels and therefore correspond to electromagnetic radiation with the same energy (1.9 eV).

9 B. Transition N is the result of a hydrogen atom absorbing 1 eV. As it increases in energy we know it is absorbing electromagnetic radiation and the difference in the energy states is 1 eV.

10 I; II; VI. Electrons transition to higher energy levels when they absorb electromagnetic radiation.

11 III; IV; V. Electrons emit electromagnetic radiation when they move to a lower energy level.

Deconstructed exam-style question

12 a C. Electrons changing energy levels does not require the acceleration of charged particles, but does release electromagnetic radiation. Options A and B are incorrect as thermal radiation is due to the acceleration of charged particles as is synchrotron radiation (option D).

b D. Energy is conserved through the release of electromagnetic radiation when electrons move from higher to lower energy levels.

c [The classmate’s statement is incorrect.[1]][Emission of electromagnetic radiation can also occur when electrons change from a higher to a lower stable energy level within an atom.[2]][This is not a result of the acceleration of a charged particle.[3]]

- I have explicitly addressed whether the classmate is correct.[1]
- I have used the relevant theory: producing light from electron transitions.[2]
- I have related my answer to the context of the question.[3]

Exam-style questions

This lesson

13 B (1 MARK)

14 **a** Electromagnetic radiation is released at a tangent to the path of the electrons. (1 MARK)

b [The bending magnets use the electromagnetic force to accelerate the electrons.[1]] [The electrons are travelling in a circle, so they are changing their direction and therefore their velocity. Since a changing velocity is acceleration, the electrons are accelerating.[2]]

- I have explicitly addressed the electromagnetic force.[1]
- I have explicitly addressed why the electrons are accelerating.[2]

15 [Light is produced by the acceleration of a charged particle[1]] [through the creation of a changing electric field and an associated changing magnetic field.[2]]

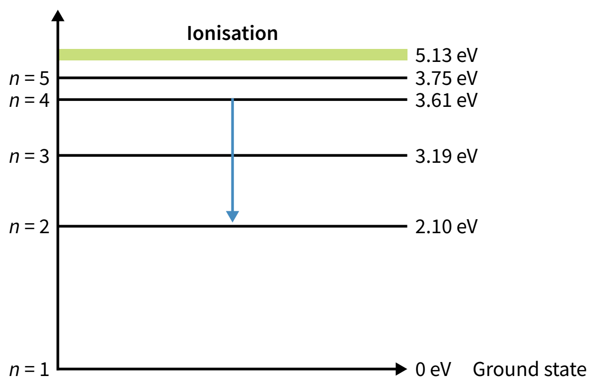
- I have explicitly addressed the motion of charged particles.[1]
- I have used the relevant theory: production of electromagnetic radiation.[2]

16 **a** $E_{released} = \Delta E = E_3 - E_1 = 3.19 - 0 = 3.19$ eV (1 MARK)

$E_{released} = \Delta E = E_2 - E_1 = 2.10 - 0 = 2.10$ eV (1 MARK)

$E_{released} = \Delta E = E_3 - E_2 = 3.19 - 2.10 = 1.09$ eV (1 MARK)

b



- I have drawn an arrow downwards to indicate emission.
- I have drawn an arrow from the third excited state ($n = 4$) to the first excited state ($n = 2$).

c [It is not possible[1]] [because there is no difference of 2.2 eV between electron energy levels, and radiation can only be emitted with an energy equal to the difference between two levels.[2]]

- I have explicitly addressed whether the observation is possible.[1]
- I have used the relevant theory: discrete energy transitions.[2]

17 [A synchrotron accelerates charged particles around a circular ring through the use of powerful magnets.[1]] [When charged particles accelerate they release electromagnetic radiation (light).[2]] [As such, when charged particles change directions as a result of the synchrotron's bending magnets they produce large amounts of light.[3]]

- I have explicitly addressed the movement of charged particles around a circular ring.[1]
- I have used the relevant theory: electromagnetic radiation by the acceleration of charged particles.[2]
- I have explicitly addressed the production of light in a synchrotron.[3]

18 [Electrons exist around a nucleus a nucleus with discrete energy levels.[1]] [When atoms absorb energy as electromagnetic radiation, electrons can become excited and go to a higher energy level.[2]] [When electrons return to a lower energy level, the difference in energy between the higher and lower energy levels is released as electromagnetic radiation in order to conserve energy.[3]]

- I have explicitly addressed that electrons exist in discrete energy levels.[1]
- I have referenced absorption of electromagnetic radiation.[2]
- I have used the relevant theory: emission of electromagnetic radiation as a result of electrons moving to a lower energy level.[3]

Previous lessons

19 $V = IR \therefore 40 = I \times (12 + 50)$ (1 MARK)

$I = 0.65$ A (1 MARK)

This content was covered in Lesson 4B.

20 $n = \frac{T}{t_{1/2}} = \frac{31.62}{5.27} = 6$ half-lives (1 MARK)

$N = N_0 \times \left(\frac{1}{2}\right)^n = 8.0 \times \left(\frac{1}{2}\right)^6 = 0.125$ kg (1 MARK)

0.125 kg of cobalt-60 will remain after 30 years.

This content was covered in Lesson 6C.

Key science skills

21 **a** [Precision is a measure of the spread of recorded values.[1]] [Emma's results have a range of 7 nm, whilst George's results range over 14 nm.[2]] [Therefore Emma's results are more precise.[3]]

- I have used the relevant theory: precision.[1]
- I have referred to the provided data in my answer.[2]
- I have explicitly addressed which results are more precise.[3]

b [Accuracy is a measure of how close the measurements are to the 'true' value of the quantity being measured.[1]][Emma's average measurement was 2 nm above the true value whilst George's average was 1 nm below the true value.[2]][Therefore George's measurements are more accurate.[3]]

- I have used the relevant theory: accuracy.[1]
- I have referred to the provided data in my answer.[2]
- I have explicitly addressed which results are more accurate.[3]

c $measurement\ uncertainty = \pm\frac{1}{2} \times smallest\ increment = \pm 0.5$ nm (1 MARK)

7C The origin of the Universe

Theory review questions

1 hot; dense; fundamental forces; particles; baryons; Big Bang nucleosynthesis

2 **a** Four fundamental forces unified

b Relatively rapid expansion of space

c Lepton formation and annihilation; Quark formation and annihilation

d Neutral atom formation; Light of the CMB generated

3 A. Radiation from the CMB reaching us in the future will have travelled for a longer time and distance. As the Universe will have continued to expand the radiation will be redshifted further, increasing its wavelength.

4 C. $v \propto d$, so an object four times further away would be expected to recede at four times the rate.

5 A. The recession is uniform in all directions, suggesting that space is expanding uniformly. This observation is true everywhere in the Universe, since there is no centre of the Universe for the expansion to be centred around.

6 D. This statement is consistent with the Big Bang Theory and supported by observations of Hubble's law. There is nothing beyond the Universe for it to grow into.

7 I; II; III

These options are all evidence-based observations that align with the predictions of the Big Bang Theory.

8 B. $\frac{7.0 \times 10^5}{6.4 \times 10^3} \simeq 1 \times 10^{5-3} = 10^2$

Deconstructed exam-style question

9 **a** C

b B. $1\frac{\text{ls}}{\text{s}} = \frac{3.0 \times 10^8 \text{ m}}{\text{s}} = 3.0 \times 10^8 \text{ m s}^{-1}$

c A. $v_B = \frac{V \text{ ls}}{300 \text{ s}} \times \frac{3.0 \times 10^8 \text{ m}}{\text{ls}} = \frac{V}{300} \times 3 \times 10^8 \text{ m s}^{-1}$

d C

$v = H_0 d$

$H_0 = \frac{v}{d} = \frac{v_A}{d_A} = \frac{v_B}{d_B} \therefore \frac{distance_B}{distance_A} = \frac{v_B}{v_A}$

e $v_A = V\frac{\text{km}}{\text{s}} \times \frac{1000 \text{ m}}{\text{km}} = V \times 10^3 \text{ m s}^{-1}$ (1 MARK)

$v_B = \frac{V \text{ ls}}{300 \text{ s}} \times \frac{3.0 \times 10^8 \text{ m}}{\text{ls}} = V \times 10^6 \text{ m s}^{-1}$ (1 MARK)

$v = H_0 d$

$H_0 = \frac{v}{d} = \frac{v_A}{d_A} = \frac{v_B}{d_B}$

$\frac{d_B}{d_A} = \frac{v_B}{v_A} = \frac{V \times 10^6}{V \times 10^3}$ (1 MARK)

$\frac{d_B}{d_A} = 10^3$ (1 MARK)

Star *B* is 1000 times further away than star *A*.

Exam-style questions

This lesson

10 B (1 MARK)

$\frac{3 \times 10^{18}}{1.5 \times 10^{11}} = 2 \times 10^7$

11 [The Big Bang predicts that the Universe is expanding in all directions.[1]][Measurements of the velocities of distant astronomical objects have been found to be proportional to their distance from us, and receding (Hubble's law).[2]][The fact that their recessional velocities only depend on distance and not direction suggests a uniform expansion, providing evidence for the Big Bang Theory.[3]]

OR

[The Big Bang Theory predicts that there was a time when electrons became bound to atomic nuclei (recombination) resulting in a burst of light being emitted in the form of a black body spectrum.[1]][The cosmic microwave background is an observed faint black body spectrum that is uniform in all directions.[2]][Since this is the expected form the light from recombination which has travelled through expanding space from the edge of the observable Universe, it is evidence for the Big Bang Theory.[3]]

OR

[The Big Bang Theory predicts that in the early Universe there was only a very short time period in which nuclear fusion could occur, leading to calculable ratios of light elements in undisturbed regions of matter.[1]][By observing light from very distant matter, and hence far into the past, we can measure the abundance of light nuclei.[2]][The observed abundances align very closely to what the theory predicts, and hence provide evidence for the Big Bang Theory.[3]]

- I have explicitly stated a prediction of the Big Bang Theory.[1]
- I have referenced the observational evidence for this prediction.[2]
- I have justified my answer with the relevant theory: evidence for the Big Bang.[3]

12 [Arno is incorrect and Robert is correct.[1]][The cosmic microwave background is the result of recombination, during a phase when the early Universe was very homogeneous.[2]][As a result it is nearly uniform in every direction. Additionally there is no centre for the expansion of the Universe to look at.[3]]

- I have explicitly stated who is correct.[1]
- I have justified my answer with the relevant theory: cosmic microwave background.[2]
- I have referenced how the cosmic microwave background is consistent in all directions.[3]

13 **a** $v = H_0 d$

$v = 2.27 \times 10^{-18} \times 2.4 \times 10^{19} \times 10^3$ (1 MARK)

$v = 5.448 \times 10^4 = 5.4 \times 10^4$ m s^{-1} (1 MARK)

b [The Andromeda galaxy is relatively close to Earth,[1]][so its motion relative to us is dominated by the effects of gravity, rather than the expansion of space.[2]][Since Hubble's law only considers the expansion of space, it fails to account for these more dominant effects at closer distances.[3]]

- I have referred to the distance between the Andromeda galaxy and Earth.[1]
- I have explicitly stated why there is a discrepancy.[2]
- I have used the relevant theory: Hubble's law's accuracy over different scales.[3]

14 [Nearly all of the matter and antimatter formed in the early Universe was annihilated.[1]][However, due to an unknown process, there was slightly more matter than antimatter.[2]][This excess of matter is what composes the objects of the Universe that we see today.[3]]

- I have used the relevant theory: matter and antimatter in the early Universe.[1]
- I have explicitly addressed that there was an imbalance in matter and antimatter.[2]
- I have related my answer to the context of the question.[3]

15 [Measuring the rate of expansion of the Universe with nearby objects is ineffective since gravitational effects will cause objects to be drawn to one another rather than recede.[1]][Hence the relative motion will be dominated by motion through space, rather than the expansion of space.[2]]

- I have referenced why uniform expansion does not hold on small scales.[1]
- I have explicitly addressed why there would be inaccuracies in measuring nearby objects.[2]

16 [This model of an explosive Big Bang is incorrect.[1]][It would necessitate that everything is moving away from some central point.[2]][Instead, what scientists have observed is that everything is receding away from everything else, suggesting there is no central point for the expansion.[3]]

- I have explicitly addressed whether the model is correct.[1]
- I have referred to the implication of the explosive Big Bang model.[2]
- I have used the relevant theory: properties of the Universe's expansion.[3]

Previous lessons

17 $V = IR$

$12 = 8.3 \times R$ (1 MARK)

$R = 1.446 = 1.4\ \Omega$ (1 MARK)

This content was covered in Lesson 4B.

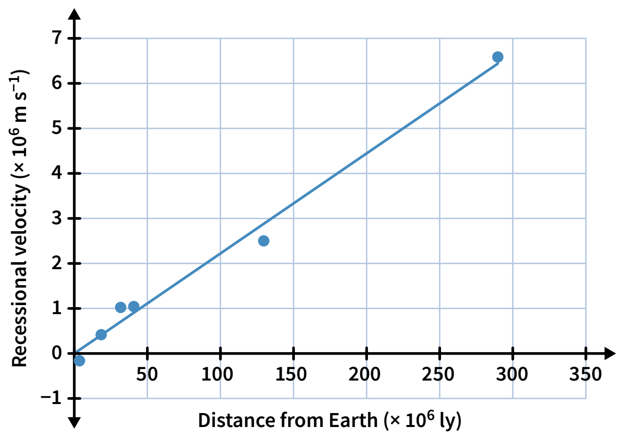
18 [William is correct and Ernest is incorrect.[1]][While a sheet of paper would be enough to prevent the penetration of alpha particles, since they penetrate poorly, it would not stop beta radiation.[2]][A thin layer of aluminium would prevent the penetration of both alpha and beta radiation, hence aluminium would be an appropriate choice of shielding.[3]]

- I have explicitly addressed who is correct.[1]
- I have related my answer to the context of the question.[2]
- I have used the relevant theory: the different forms of radiation's ability to penetrate each of the shielding materials.[3]

This content was covered in Lesson 6D.

Key science skills

19 **a**



- I have plotted distance on the horizontal axis and velocity on the vertical axis.
- I have included axis labels and appropriate units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each data point: (2.73,−0.179), (17.3, 0.408), (31.1, 1.02), (40.0, 1.05), (129, 2.50), (290, 6.61).
- I have included a line of best fit.

b $gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{(6.0 - 0.0) \times 10^6}{(270 - 0) \times 10^6} = 0.022 \text{ m s}^{-1} \text{ ly}^{-1}$ (1 MARK)

$\frac{0.022 \text{ m}}{\text{s ly}} \times \frac{1 \text{ ly}}{9.46 \times 10^{15} \text{ m}} = 2.3 \times 10^{-18} \text{ s}^{-1}$ (1 MARK)

A range of values between 2.2×10^{-18} and 2.4×10^{-18} is acceptable, depending on the line of best fit drawn.

c The gradient is the ratio between an object's distance and its recessional velocity, or the Hubble constant. (1 MARK)

Chapter 7 Review

Section A

1 B. The fusion of protons will result in a greater change in binding energy per nucleon than the fission of uranium-235. Since there are approximately the same number of nucleons in a gram of protons and a gram of uranium-235, the fusion of protons will release more energy.

2 C. An electromagnetic wave is oscillating perpendicular electric and magnetic fields.

3 B. Charged particles (commonly electrons) are accelerated within the storage ring to near the speed of light.

4 D. Cosmic microwave background radiation, redshift, and the near-uniform density of matter across the observable Universe are all pieces of evidence that support the Universe expanding from a hot and dense initial state.

5 C. There was an excess of matter left after the hadron epoch.

Section B

6 $E = 8.7 \text{ MeV} = 8.7 \times 10^6 \text{ eV} = 8.7 \times 10^6 \times 1.6 \times 10^{-19} = 1.39 \times 10^{-12} \text{ J}$

$\Delta E = \Delta mc^2 \therefore 1.39 \times 10^{-12} = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 1.54 \times 10^{-29} = 1.5 \times 10^{-29} \text{ kg}$ (1 MARK)

7 [Penzias and Wilson observed the cosmic microwave background.[1]] [This radiation is the highly redshifted light that was produced when neutral atoms were first formed, during recombination.[2]] [This observation suggested that the Universe was once significantly hotter and denser than it is today, and has undergone significant expansion since then.[3]] [Since these are key predictions of the Big Bang, they provide evidence for it.[4]]

- I have explicitly stated what Penzias and Wilson observed.[1]
- I have used the relevant theory: the cosmic microwave background.[2]
- I have explicitly stated the observational evidence provided by the cosmic microwave background.[3]
- I have explicitly addressed how this provides evidence for the Big Bang.[4]

8 $\Delta m = (5.0082709 \times 10^{-27} + 6.6464815 \times 10^{-27})$
$- (1.6749275 \times 10^{-27} + 9.9883519 \times 10^{-27}) = -8.5270 \times 10^{-30} \text{ kg}$ (1 MARK)

$\Delta E = \Delta mc^2 = -8.5270 \times 10^{-30} \times (3.0 \times 10^8)^2 = -7.6743 \times 10^{-13}$
$= -7.7 \times 10^{-13} \text{ J}$ (1 MARK)

7.7×10^{-13} J of energy is released in the reaction. (1 MARK)

9 **a** $E_{photon} = E_{absorbed} = \Delta E = E_4 - E_2 = 12.8 - 10.2 = 2.6 \text{ eV}$ (1 MARK)

b $E_{released} = \Delta E = E_4 - E_3 = 12.8 - 12.1 = 0.7 \text{ eV}$;
$E_{released} = \Delta E = E_4 - E_2 = 12.8 - 10.2 = 2.6 \text{ eV}$ (1 MARK)

$E_{released} = \Delta E = E_4 - E_1 = 12.8 - 0 = 12.8 \text{ eV}$;
$E_{released} = \Delta E = E_3 - E_2 = 12.1 - 10.2 = 1.9 \text{ eV}$ (1 MARK)

$E_{released} = \Delta E = E_3 - E_1 = 12.1 - 0 = 12.1 \text{ eV}$;
$E_{released} = \Delta E = E_2 - E_1 = 10.2 - 0 = 10.2 \text{ eV}$ (1 MARK)

10 [Ben is not correct.[1]] [The magnets in a synchrotron are used to accelerate charged particles like electrons because charged particles release electromagnetic radiation when they accelerate.[2]] [Electrons being excited and then dropping down to a lower energy level is how light is produced within an atom.[3]]

- I have explicitly addressed whether Ben is correct.[1]
- I have used the relevant theory: electromagnetic radiation by the acceleration of charged particles.[2]
- I have used the relevant theory: energy transitions between energy levels of an atom.[3]

11 $d = 7.57 \times 10^8 \times 9.46 \times 10^{15} = 7.16 \times 10^{24} \text{ m}$ (1 MARK)

$v = H_0 d = 2.27 \times 10^{-18} \times 7.16 \times 10^{24} = 1.63 \times 10^7 \text{ m s}^{-1}$ (1 MARK)

Yes, galaxies at distances greater than 5×10^6 light-years are generally moving away from us. (1 MARK)

12 **a** $m_{nucleons} = 7 \times 1.6726 \times 10^{-27} + 7 \times 1.6749 \times 10^{-27}$
$= 2.34325 \times 10^{-26} \text{ kg}$ (1 MARK)

$\Delta m = m_{nucleons} - m_{nitrogen} = 2.34325 \times 10^{-26} - 2.3252 \times 10^{-26}$
$= 1.81 \times 10^{-28} \text{ kg}$ (1 MARK)

b $\Delta E = \Delta mc^2 = 1.81 \times 10^{-28} \times (3.0 \times 10^8)^2 = 1.6 \times 10^{-11} \text{ J}$ (1 MARK)

13 [Before stars formed, there were few sources of light.[1]] [The early Universe's density was near-uniform,[2]] [as such it took a long time before matter was able to pull itself together to become dense enough to form stars.[3]]

- I have used the relevant theory: characteristics of the dark ages.[1]
- I have explicitly addressed the conditions of the early Universe that led to the dark ages being so long.[2]
- I have used the relevant theory: how the first stars formed.[3]

Unit 1, AOS 3 Review

Section A

1 A. Ionising ability is greater for radiation with greater mass and charge.

This content was covered in Lesson 6D.

2 D

This content was covered in Lesson 6A.

3 C. Electromagnetic radiation is produced when a **charged** particle **accelerates**.

This content was covered in Lesson 7B.

4 D. The strangeness of the particle is equal to the sum of the strangeness of each of the quarks.

This content was covered in Lesson 6A.

5 B. The isotopes with more than 57 neutrons have mass numbers of 102 and 104 and have a combined abundance of approximately 50%.

This content was covered in Lesson 6B.

Section B

6 The decay chain can be written as ${}^{227}_{89}Ac \rightarrow {}^{207}_{82}Pb + m \times {}^{4}_{2}\alpha + n \times {}^{0}_{-1}e$ (1 MARK)

Use the mass number to determine the number of alpha particles released:

$227 = 207 + 4 \times m$

$m = \frac{227 - 207}{4} = 5$ (1 MARK)

Use the atomic number to determine the number of beta minus particles (electrons) released:

$89 = 82 + 5 \times 2 - n$

$n = 3$ (1 MARK)

There are 5 alpha particles and 3 beta minus particles released.

This content was covered in lesson 6D.

7 **a** $A = A_0\left(\frac{1}{2}\right)^n \therefore 1.0 \times 10^2 = 1.28 \times 10^4 \times \left(\frac{1}{2}\right)^n$ (1 MARK)

$\left(\frac{1}{2}\right)^n = \frac{1}{128} = \left(\frac{1}{2}\right)^7 \therefore n = 7$ (1 MARK)

Therefore Axel would have to wait $7 \times 1.19 = 8.3$ days. (1 MARK)

This content was covered in Lesson 6C.

b $m = m_0\left(\frac{1}{2}\right)^n \therefore 15.0 \times 10^{-3} = 60.0 \times 10^{-3} \times \left(\frac{1}{2}\right)^n$ (1 MARK)

$\left(\frac{1}{2}\right)^n = \frac{1}{4} = \left(\frac{1}{2}\right)^2 \therefore n = 2$ (1 MARK)

$n = \frac{T}{t_{1/2}} \therefore 2 = \frac{23.0}{t_{1/2}}$

$t_{1/2} = 11.5 \text{ days} = 11.5 \times 24 = 276 \text{ hours}$

The half-life of phosphorus-32 is 276 hours. (1 MARK)

This content was covered in Lesson 6C.

c $\Delta E = \Delta mc^2 = (60.0 - 15.0) \times 10^{-3} \times (3.0 \times 10^8)^2 = 4.1 \times 10^{15}$ J (1 MARK)

This content was covered in Lesson 7A.

d [The passing of one half-life means that there is a 50% chance for any given nuclide to decay in that period. As such, approximately half of the original sample will have undergone radioactive decay.[1]][Axel is incorrect, because he thinks that exactly (instead of approximately) half of the nuclides will decay. Axel's claim is akin to saying that flipping two coins will always give one head and one tail.[2]]

- I have used the relevant theory: half-lives' probabilistic nature.[1]
- I have explicitly stated why Axel is incorrect.[2]

This content was covered in Lesson 6C.

8 **a** [The wavelengths of light emitted by the galaxy appear to have all been increased, which is why no wavelengths of light below 400 nm are observed.[1]][As such, it is likely that the reason for the discrepancy is that the light emitted by the galaxy was redshifted as it travelled through expanding space towards Earth, which would increase its wavelength.[2]]

- I have referenced that the wavelengths of light appear to have all been increased.[1]
- I have used the relevant theory: cosmological redshifting of light.[2]

This content was covered in Lesson 7C.

b $v = H_0 d \therefore 4.0 \times 10^7 = 2.27 \times 10^{-18} \times d$

$d = 1.76 \times 10^{25}$ m (1 MARK)

Convert to light-years to find time elapsed:

$1.76 \times 10^{25} \text{ m} = \frac{1.76 \times 10^{25}}{3 \times 10^8 \times 60 \times 60 \times 24 \times 365.25}$

$= 1.86 \times 10^9$ light-years (1 MARK)

Therefore it will be 1.86×10^9 years before the event can be observed on Earth. (1 MARK)

This content was covered in Lesson 7C.

9 **a** [In order for an atom's nucleus to separate into its unbound nucleons, the nucleons need to gain energy in order to overcome the strong nuclear force keeping them together.[1]][From $E = mc^2$, we know that an increase in a particle's energy increases its mass.[2]][So, since the unbound nucleons have more energy, they will have a larger total mass than the original nucleus.[3]]

- I have referenced the energy required to overcome the strong nuclear force.[1]
- I have used the relevant theory: mass-energy equivalence.[2]
- I have explicitly addressed why the original atom will be lighter than the unbound nucleons.[3]

This content was covered in Lesson 7A.

b $\textit{mass of nucleons} = 1.67 \times 10^{-27} \times 235 = 3.9339 \times 10^{-25}$ kg

$\Delta E = \Delta mc^2 \therefore \Delta E = (3.9339 - 3.902) \times 10^{-25} \times (3 \times 10^8)^2$

$\Delta E = 2.871 \times 10^{-10}$ J (1 MARK)

$\textit{binding energy per nucleon} = \frac{\textit{binding energy}}{\textit{number of nucleons}} = \frac{2.871 \times 10^{-10}}{235}$ (1 MARK)

$\textit{binding energy per nucleon} = 12.2 \times 10^{-13}$ J

This content was covered in Lesson 7A.

c The mass numbers on either side of the equation must balance

$235 + 1 = 142 + 90 + y$ (1 MARK)

$y = 4$ (1 MARK)

This content was covered in Lesson 7A.

d *binding energy = number of nucleons × binding energy per nucleon*

$E_{xenon} = 142 \times 13.3 \times 10^{-13} = 1.889 \times 10^{-10}$ J (1 MARK)

$E_{strontium} = 90 \times 13.9 \times 10^{-13} = 1.251 \times 10^{-10}$ J (1 MARK)

$E_{uranium} = 235 \times 12.2 \times 10^{-13} = 2.871 \times 10^{-10}$ J (1 MARK)

Per atom of uranium-235, $\Delta E = E_{xenon} + E_{strontium} - E_{uranium}$

$\Delta E = (1.889 - 1.251 - 2.871) \times 10^{-10} = 2.69 \times 10^{-11}$ J (1 MARK)

Number of uranium-235 atoms required $= \frac{3.5 \times 10^{6}}{2.69 \times 10^{-11}}$

$= 1.30 \times 10^{17}$ atoms

Since there is one neutron on the left side of the equation, and four on the right, the net increase in neutrons with each reaction is three. Therefore the number of neutrons released is $3 \times 1.30 \times 10^{17} = 3.9 \times 10^{18}$ neutrons. (1 MARK)

This content was covered in Lesson 7A.

10 [The blue curve represents the strong nuclear force and the red curve represents the electrostatic force.[1]] [As the separation between two given protons decreases, the strong force is initially attractive and has a greater magnitude than the electrostatic repulsion. This corresponds to the nuclear separation of stable nuclei.[2]] [Eventually the strong force weakens with decreasing separation while the electrostatic force continues to increase, resulting in the forces eventually cancelling out. This corresponds to the nuclear separation in radioactive nuclei.[3]]

- I have explicitly stated which force each of the curves represents.[1]
- I have referenced the behaviour of the forces for larger nuclear separations.[2]
- I have referenced the behaviour of the forces for smaller nuclear separations.[3]

This content was covered in Lesson 6B.

11 [Both baryons and mesons are classified as hadrons, which are subatomic particles composed of two or more quarks.[1]] [Baryons consist of an odd number of quarks (usually three) whereas mesons are made of only two quarks.[2]] [Baryons include stable particles like the proton and neutron, however all mesons are extremely unstable.[3]]

- I have explicitly stated that both baryons and mesons are hadrons.[1]
- I have explicitly stated that baryons contain an odd number of quarks and mesons contain two quarks.[2]
- I have referenced that baryons include stable particles like the proton/neutron and that all mesons are unstable.[3]

This content was covered in Lesson 6A.

12 [The Big Bang Theory predicts that there was a short period of time in which the conditions of the Universe would allow for nuclear fusion reactions to occur.[1]] [We can observe ancient light from undisturbed regions of the Universe to make measurements of the ratios of nuclei as they were at this time.[2]] [The measured abundances all agree with theoretical calculations and hence provide strong evidence to support the Big Bang Theory.[3]]

- I have explicitly addressed Big Bang nucleosynthesis.[1]
- I have used the relevant theory: the predictability of the ratios of nuclei in the early Universe.[2]
- I have explicitly addressed how this provides evidence for the Big Bang Theory.[3]

This content was covered in Lesson 7C.

13 **a** [In order for a photon of a given energy to be emitted or absorbed, its energy has to be precisely equal to the difference between two of hydrogen's discrete energy levels.[1]] [Since the difference between the $n = 1$ and $n = 3$ levels is 12.1 eV, this energy of light can be absorbed.[2]] [However, there are no two energy levels that differ by 10.0 eV, so this energy of light cannot be emitted.[3]]

- I have used the relevant theory: energy of photon equal to the difference of energy levels.[1]
- I have explicitly addressed the difference between the $n = 1$ and $n = 3$ energy levels.[2]
- I have explicitly addressed the lack of an energy difference of 10.0 eV between any two energy levels.[3]

This content was covered in Lesson 7B.

b $n = 5$:

(13.1 − 12.8) = 0.3 eV, (13.1 − 12.1) = 1.0 eV, (13.1 − 10.2) = 2.9 eV (1 MARK)

$n = 4$:

(12.8 − 12.1) = 0.7 eV, (12.8 − 10.2) = 2.6 eV (1 MARK)

$n = 3$:

(12.1 − 10.2) = 1.9 eV (1 MARK)

This content was covered in Lesson 7B.

8A Describing motion

Theory review questions

1 D. When a path includes a change in direction, displacement is not equal to distance.

2 II; III

Velocity and speed are different when there is a change in direction over the time interval.

3 Displacement; velocity; speed; velocity; time

4 I-B; II-A; III-B; IV-E; V-C; VI-D

Deconstructed exam-style question

5 **a** B **b** C **c** D

d A **e** B

f $v = \frac{\Delta s}{\Delta t}$

$\therefore v_{flat} = \frac{s_{flat}}{t_{flat}}, t_{flat} = \frac{s_{flat}}{6.0}$

$v_{hills} = \frac{s_{hills}}{t_{hills}}, t_{hills} = \frac{s_{hills}}{4.0}$ (1 MARK)

$t_{total} = t_{flat} + t_{hills} + t_{break}$ $\therefore 9.0 = t_{flat} + t_{hills} + 1$ (1 MARK)

Distance hiked up hills is half the distance hiked on flat ground, $\therefore s_{flat} = 2s_{hills}$ (1 MARK)

$9.0 = \frac{2s_{hills}}{6.0} + \frac{s_{hills}}{4.0} + 1$ $\therefore s_{hills} = \frac{96}{7} = 14$ km (1 MARK)

$s_{flat} = 2s_{hills} = 2 \times 13.7 = 27$ km

$s_{total} = s_{flat} + s_{hills} = 14 + 27 = 41$ km

$v_{avg} = \frac{s_{total}}{t_{total}} = \frac{41}{9.0} = 4.6$ km h^{-1}

Since they travel from *A* to *B*, their average velocity is 4.6 km h^{-1} to the east. (1 MARK)

Exam-style questions

This lesson

6 $v = \frac{\Delta s}{\Delta t} = \frac{100}{20} = 5.0$ m s^{-1} (1 MARK)

7 **a** 25 + 25 = 50 m (1 MARK)

b Since he starts and ends at the same place, *s* = 0 m. (1 MARK)

c $v = \frac{\Delta s}{\Delta t} = \frac{0}{40} = 0$ m s^{-1} (1 MARK)

8 $\Delta s = \sqrt{10^2 + 7^2} = \sqrt{149} = 12.21$ km (1 MARK)

$\Delta t = 100$ minutes $= \frac{100}{60} = 1.67$ hours (1 MARK)

$v = \frac{\Delta s}{\Delta t} = \frac{12.21}{1.67} = 7.3$ km h^{-1} (1 MARK)

9 [Velocity and speed are similar in the sense that they quantify the rate at which an object moves over time.[1]][However, velocity is a vector quantity whilst speed is a scalar quantity.[2]][Also, velocity is the change in displacement with respect to time, whereas speed is the change in distance travelled with respect to time.[3]][When an object does not change direction, the magnitudes of these two values will be the same, however when it does, they will no longer be equal.[4]]

- I have explicitly addressed how velocity and speed are similar.[1]
- I have explicitly addressed that velocity is a vector quantity and speed is a scalar quantity.[2]
- I have explicitly addressed how velocity and speed are different.[3]
- I have justified my answer by describing when velocity and speed are different.[4]

10 12 km = 12 × 10^3 m

60 km h^{-1} $= \frac{60}{3.6}$ m s^{-1} = 16.67 m s^{-1} (1 MARK)

$\Delta t = \frac{\Delta s}{v} = \frac{12 \times 10^3}{16.67} = 7.2 \times 10^2$ s (1 MARK)

OR

$t = \frac{\Delta s}{v} = \frac{12}{60} = \frac{1}{5}$ hours $= \left(\frac{1}{5} \times 60 \times 60\right) = 7.2 \times 10^2$ s (2 MARKS)

11 **a** displacement from *B* to *C* = 2 × *r* = 2 × 1.5 = 3 km (1 MARK)

$t = 100$ s $= \frac{100}{60 \times 60} = 0.0278$ hours (1 MARK)

$v = \frac{\Delta s}{\Delta t} = \frac{3}{0.0278} = 1.1 \times 10^2$ km h^{-1} (1 MARK)

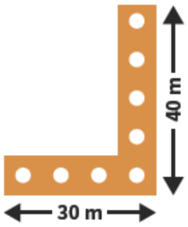
The driver has exceeded the limit. (1 MARK)

b [The velocity is different to the speed because there is a change in direction over the time interval.[1]][This means that the displacement will be different from the distance travelled.[2]][In this case, the velocity is 108 km h^{-1}. We can find speed by calculating the distance travelled (half the circumference of a circle) and dividing by the time.

$speed = \frac{distance\ travelled}{time} = \frac{\frac{1}{2} \times 2 \times \pi \times 1.5}{0.0278} = 170$ km h^{-1}.[3]]

- I have explicitly addressed why the velocity is different to the speed.[1]
- I have explicitly addressed that the displacement and distance are different.[2]
- I have justified my answer using relevant calculations.[3]

12

Description	Sketch	Non-zero acceleration?
They start stationary and run along a straight path to reach a velocity of 10 m s^{-1} after 4 seconds.		Yes, acceleration is to the right.
They travel 30 metres east and then 40 metres north at a fixed speed of 10 m s^{-1}.		Hansel and Gretel go from having a velocity to the right to a velocity up the page. There is therefore a change in velocity and therefore the acceleration is non-zero.
They run with a constant speed around a semicircular path with a radius of 10 metres in 5 seconds.		The spacing between each crumb is constant, however there is clearly a change in direction. Therefore the acceleration is non-zero.
They slow down from 10 m s^{-1} to 5 m s^{-1} in a straight line over 5 seconds as they near the end of the path.		The spacing between consecutive crumbs decreases, which means the acceleration is non-zero. Acceleration is towards the left.

Previous lessons

13 $R = \frac{\rho l}{A}$ $\therefore 8 = \frac{1.724 \times 10^{-8} \times 20}{A}$ (1 MARK)

$A = 4.32 \times 10^{-8}\ m^2$ (1 MARK)

$A = \pi r^2$ $\therefore 4.32 \times 10^{-8} = \pi \times r^2$ (1 MARK)

$r = 1.2 \times 10^{-4}$ m (1 MARK)

This content was covered in Lesson 4B.

14 [One type of radioactive decay is alpha radiation.[1]][This is the emission of an alpha particle, which consists of two protons and two neutrons.[2]][Alpha radiation has the highest ionisation ability but the lowest penetrating ability.[3]]

OR

[One type of radioactive decay is beta radiation.[1]][This is the emission of an electron or a positron.[2]][Beta radiation has a relatively moderate ionisation ability and relatively moderate penetrating ability.[3]]

OR

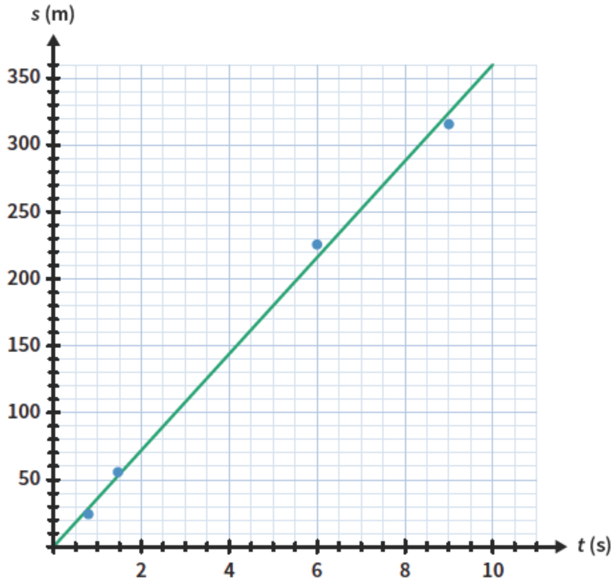
[One type of radioactive decay is gamma radiation.[1]][This is the emission of high frequency electromagnetic waves.[2]][Gamma radiation has the lowest ionisation ability but the highest penetrating ability.[3]]

- I have named one of the three types of radioactive decay: alpha, beta or gamma radiation.[1]
- I have referenced what the type of radioactive decay consists of.[2]
- I have referenced the ionisation and penetrating ability of the type of radioactive decay.[3]

This content was covered in Lesson 6D.

Key science skills

15 a



- I have correctly labelled both axes and included units.
- I have used an appropriate and consistent scale on the axes.
- I have correctly plotted each point of data.
- I have included a line of best fit.

b $gradient = \frac{rise}{run} = \frac{\Delta s}{\Delta t} = v$. The gradient represents the magnitude of the velocity. (1 MARK)

Use any two points on the line of best fit:

$gradient = \frac{360 - 0}{10 - 0} = 36$ m s^{-1} (1 MARK)

Depending on the line of best fit drawn, answers between 34 m s^{-1} and 38 m s^{-1} are acceptable.

8B Graphing motion

Theory review questions

1 acceleration; velocity; does not have to

2 II; III

The acceleration over P_2 is zero so the instantaneous velocity is equal to the average velocity. The magnitude of the area under a velocity-time graph represents the distance travelled.

3 I

Acceleration is the change in velocity over time, so the velocity over interval *R* does not have to be zero.

4 a *D*

b *C*

c *A*; *E*

d *B*; *F*

5 B. Displacement is equal to the signed area under the graph. Subtract *P* and *R* and add *Q*.

6 a C b D c A d B

7 I; III

The velocity-time graph tells us that the gradient of the displacement-time graph is 5. Lines II and IV do not have a gradient of 5.

Deconstructed exam-style question

8 a B b C c A d B

e Δv = *area under acceleration-time graph* = $5a$ m s^{-1} (1 MARK)

$\Delta v = v_2 - v_1 \therefore v_2 = 5a$ m s^{-1} (1 MARK)

Δs = *area under velocity-time graph* = $\frac{1}{2} \times 5a \times 5 = \frac{25}{2}a$ m (1 MARK)

$\Delta s = \frac{25}{2}a = 150 \therefore a$ m s^{-2} = 12 m s^{-2} (1 MARK)

Exam-style questions

This lesson

9 a v_{avg} = *gradient of displacement-time graph*

$v_{avg} = \frac{rise}{run} = \frac{12-0}{8-0} = 1.5$ m s^{-1} (1 MARK)

b $v_{int} = v_{avg} = 1.5$ m s^{-1} (1 MARK)

10 a a_{avg} = *gradient of velocity-time graph*

$a_{avg} = \frac{rise}{run} = \frac{0-10}{1.5-0} = -6.7$ m s^{-2}

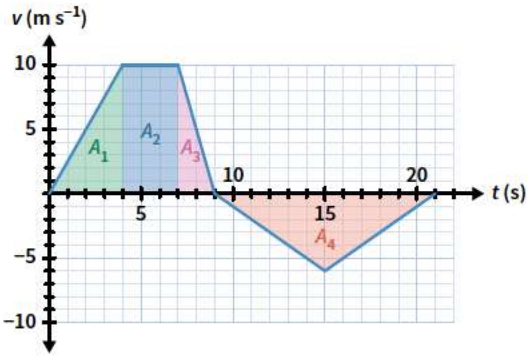
The magnitude of the average acceleration is 6.7 m s^{-2}. (1 MARK)

b Δs = *area under velocity-time graph*

$\Delta s = \frac{1}{2} \times 10 \times 1.5 = 7.5$ m (1 MARK)

The model car travels 7.5 m up the ramp before coming to a stop. (1 MARK)

11



Δs = *signed area under graph* = $A_1 + A_2 + A_3 - A_4$ (1 MARK)

$\Delta s = \left(\frac{1}{2} \times 4 \times 10\right) + (3 \times 10) + \left(\frac{1}{2} \times 2 \times 10\right) - \left(\frac{1}{2} \times 12 \times 6\right) = 24$ m (1 MARK)

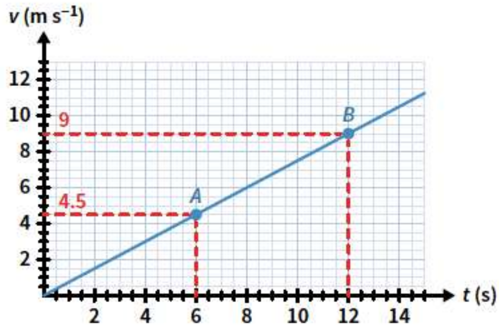
Therefore Kate finishes 24 m in front of her starting position. (1 MARK)

12 a $v_{avg} = \frac{\Delta s}{\Delta t} = \frac{7.5}{10} = 0.75$ m s^{-1} (1 MARK)

b $v_{avg} = \frac{\Delta s}{\Delta t} = \frac{0}{30} = 0$ m s^{-1} (1 MARK)

c *average speed* = $\frac{distance}{time} = \frac{7.5 + 7.5 + 7.5 + 7.5}{30} = 1.0$ m s^{-1} (2 MARKS)

13 a



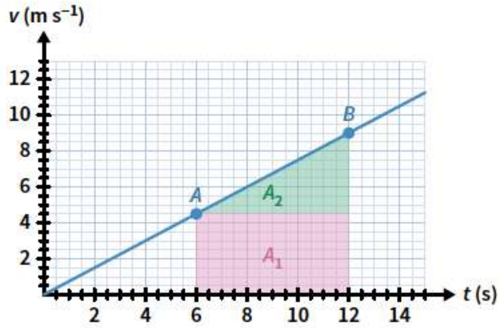
I have correctly labelled both axes and included units.

I have drawn a straight line for the velocity-time graph.

The line passes through the points (6, 4.5) and (12, 9).

b Δs = *area under graph* = $A_1 + A_2$ (1 MARK)

$\Delta s = (6 \times 4.5) + \left(\frac{1}{2} \times 6 \times 4.5\right) = 40.5 = 41$ m (1 MARK)



14 Δs = *signed area under graph*

$\Delta s = \frac{1}{2} \times 17 \times 1.73 - \frac{1}{2} \times (4.5 - 1.73) \times 27.1 = -22.8 = -23$ m (2 MARKS)

The value of h is 23 m. (1 MARK)

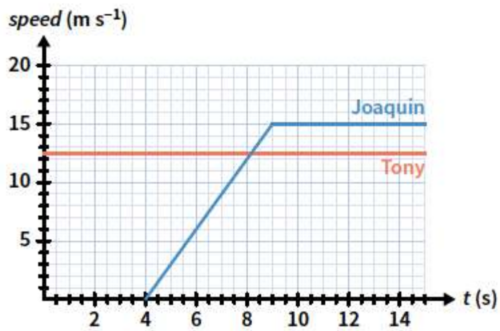
15 There are 23 squares under the curve, and each has an area of $0.5 \times 2.5 = 1.25$ m. (1 MARK)

Δs = *area under graph* = $1.25 \times 23 = 28.75$ m (1 MARK)

Therefore the car will pass the test. (1 MARK)

A range of Δs values between 26.25 m and 31.25 m is acceptable, depending on the number of squares counted.

16 a

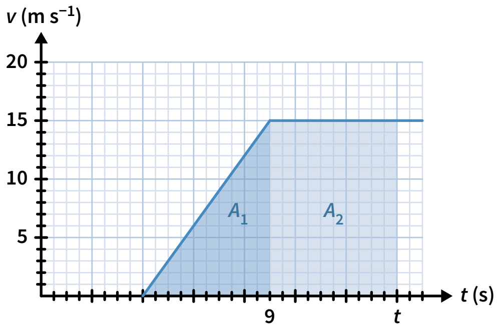


I have correctly labelled both axes and included units.

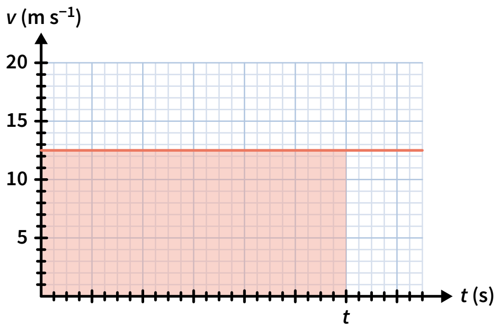
I have correctly drawn the shape of Tony's speed-time graph.

I have correctly drawn the shape of Joaquin's speed-time graph.

b When Joaquin catches up to Tony, the area under both their speed-time graphs will be equal. Suppose he catches Tony after t seconds.



$distance_{Joaquin} = A_1 + A_2 = \frac{1}{2} \times (9-4) \times 15 + 15(t-9) = 15t - 97.5$ (1 MARK)



$distance_{Tony} = 12.5t$ (1 MARK)

$15t - 97.5 = 12.5t$

$t = 39$ s (1 MARK)

OR

After 9 seconds:

$distance_{Tony} = v\Delta t = 12.5 \times 9 = 112.5$ m

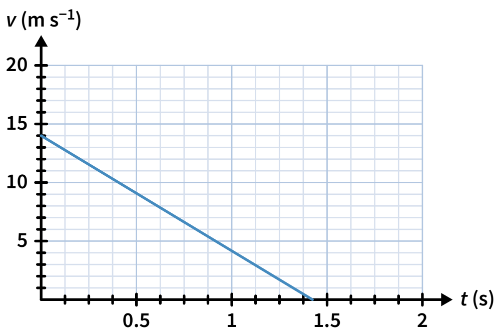
$distance_{Joaquin} = A_1 = \frac{1}{2} \times 5 \times 15 = 37.5$ m (1 MARK)

Therefore Joaquin is 112.5 − 37.5 = 75 m behind Tony.

$speed_{Joaquin} = 15$ m s^{-1}, so every second after $t = 9$ s, he will gain 2.5 m on Tony. (1 MARK)

It will therefore take $\frac{75}{2.5} = 30$ s for him to catch Tony, so the total time would be 30 + 9 = 39 s. (1 MARK)

17 **a**



- I have correctly labelled both axes and included units.
- I have used an appropriate and consistent scale on the axes.
- I have drawn a straight line for the velocity-time graph.
- The y-intercept of the line is at (0, 14.0) and the x-intercept is (1.43, 0).

b $\Delta s = area\ under\ graph = \frac{1}{2} \times 14.0 \times 1.43 = 10.0$ m. (1 MARK)

The maximum height of the ball is 10.0 m (1 MARK)

Previous lessons

18 **a** $V_{supply} = IR_T \therefore 6.0 = I \times (100 + 100 + 100)$ (1 MARK)

$I = 0.020$ A (1 MARK)

b $P = VI$

Since each resistor has equal resistance, $V_1 = 2.0$ V. (1 MARK)

$P_1 = 2.0 \times 0.020 = 0.040$ W (1 MARK)

c $V_{supply} = IR_T \therefore 6.0 = I \times (100 + 100)$

$I = 0.030$ A (1 MARK)

$P_{new} = V_1 I \therefore P_{new} = 3.0 \times 0.030 = 0.090$ W (1 MARK)

$P_{new} : P_{old} = 0.090 : 0.040 = 9 : 4$ (1 MARK)

This content was covered in Lesson 4C.

19 $m_i = m_f \therefore 9.988 \times 10^{-27} + 3.344 \times 10^{-27} = 2 \times 6.646 \times 10^{-27} + \Delta m$

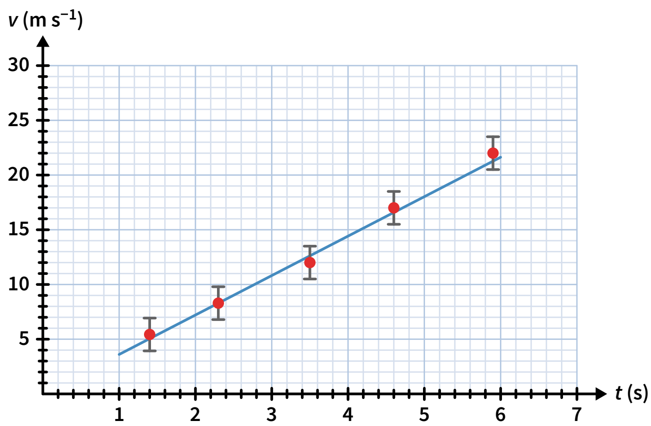
$\Delta m = 0.04 \times 10^{-27}$ (1 MARK)

$\Delta E = \Delta mc^2 = 0.04 \times 10^{-27} \times (3.0 \times 10^8)^2 = 3.6 \times 10^{-12}$ J (1 MARK)

This content was covered in Lesson 7A.

Key science skills

20



- I have correctly labelled both axes and included units.
- I have used an appropriate and consistent scale on the axes.
- I have correctly plotted each point of data.
- I have included accurate uncertainty bars.
- I have included a line of best fit that passes through all of the uncertainty bars.

8B

8C The constant acceleration equations

Theory review questions

1 C

2 **a** $s = vt - \frac{1}{2}at^2$ **OR** $v = u + at$ (by recognising that $u = -v$);

b $s = \frac{1}{2}(u + v)t$;

c $v^2 = u^2 + 2as$;

d $v = u + at$

3 **a** No. Only two variables are known: a and t.

b Yes. One variable is given, t, and two can be implied: $a = -9.8$ m s^{-2} and $v = 0$ m s^{-1} when it reaches its peak.

c Yes. Given that we are looking at vertical acceleration, $a = -9.8$ m s^{-2}.

d Yes. One variable is given, u, and two can be implied: $a = 9.8$ m s^{-2} and $s = 0$ m since it lands where it started.

Deconstructed exam-style question

4 **a** B **b** C **c** C **d** D

e B **f** A **g** A

h Given: $a = -9.8$ m s^{-2}, $s = -3$ m, $u = 6.0$ m s^{-1}; Required: t

After t_1 seconds, $v = 0$ m s^{-1}:

$v = u + at_1$

$\therefore 0 = 6.0 - 9.8t_1$, $t_1 = 0.61$ s (1 MARK)

After t_1 seconds:

$s = \frac{1}{2}(u + v)t = \frac{1}{2}(6.0 + 0) \times 0.61 = 1.8$ m

From t_1 seconds to t_2 seconds, $s = -3.0 - 1.8 = -4.8$ m:

$v^2 = u^2 + 2as$

$\therefore v = -\sqrt{0^2 + 2(-9.8)(-4.8)} = -9.7$ m s^{-1}. We know velocity must be downward and hence is negative.

$v = u + at_2$, with $v = -9.7$ m s^{-1} and $u = 0$ m s^{-1}

$\therefore -9.7 = 0 - 9.8t_2$, $t_2 = 0.99$ s (1 MARK)

$t_{total} = t_1 + t_2 = 0.61 + 0.99 = 1.6$ s (1 MARK)

The time taken for the dive is 1.6 seconds, which is less than the required 1.75 seconds. Therefore he would under-rotate. (1 MARK)

OR

$v^2 = u^2 + 2as$ (1 MARK)

$\therefore v = -\sqrt{(6.0)^2 + 2(-9.8)(-3)} = -9.7$ m s^{-1} (1 MARK)

$v = u + at$

$\therefore -9.7 = 6.0 - 9.8t$

$t = 1.6$ s (1 MARK)

The time taken for the dive is 1.6 seconds, which is less than the required 1.75 seconds. Therefore he would under-rotate. (1 MARK)

OR

$s = ut + \frac{1}{2}at^2$ (1 MARK)

$\therefore -3 = 6.0t - 4.9t^2$ (1 MARK)

Moving all variables to one side and using the quadratic formula,

$t = \frac{6.0 + \sqrt{6.0^2 - 4(4.9)(-3)}}{2 \times 4.9} = 1.6$ s (1 MARK)

The time taken for the dive is 1.6 seconds, which is less than the required 1.75 seconds. Therefore he would under-rotate. (1 MARK)

Exam-style questions

This lesson

5 Given: $u = 0$ m s^{-1}, $t = 6.0$ s, $v = 45$ m s^{-1}; Needed: s

$s = \frac{1}{2}(u + v)t$ (1 MARK)

$s = \frac{1}{2}(0 + 45) \times 6 = 135 = 1.4 \times 10^2$ m (1 MARK)

6 Given: $a = 2.50$ m s^{-2}, $v = 24.0$ m s^{-1}, $t = 10.0$ s; Needed: s

$s = vt - \frac{1}{2}at^2$ (1 MARK)

$s = 24.0 \times 10.0 - \frac{1}{2} \times 2.50 \times 10.0^2 = 115$ m (1 MARK)

7 Given: $t = 2.5$ s, $a = -9.8$ m s^{-2}, $v = -11$ m s^{-1}; Needed: u

$v = u + at$ (1 MARK)

$-11 = u + (-9.8) \times 2.5$ (1 MARK)

$u = 13.5 = 14$ m s^{-1} upwards (1 MARK)

8 **a** Given: $v = 18$ m s^{-1}, $s = -15$ m, $a = -9.8$ m s^{-2}; Needed: u

$v^2 = u^2 + 2as$ (1 MARK)

$(-18)^2 = u^2 + 2 \times (-9.8) \times (-15)$ (1 MARK)

$u = 5.5$ m s^{-1} (1 MARK)

b [Pebbles' claim is invalid.[1]][As the initial velocity of the water balloon is not equal to zero, she must have thrown the balloon, not dropped it.[2]]

I have explicitly addressed whether Pebbles' claim is true.[1]

I have referenced the initial velocity of the water balloon to support my answer.[2]

9 Given: $v = 0$ m s^{-1}, $t = 18$ s, $a = -0.35$ m s^{-2}; Needed: s

$s = vt - \frac{1}{2}at^2$ (1 MARK)

$s = 0 \times 18 - \frac{1}{2} \times (-0.35) \times 18^2 = 56.7 = 57$ m (1 MARK)

Therefore, Santush's bowl will not stop at the edge of the green and he will not win the game. (1 MARK)

10 a Given: $u_{Mavis} = v_{Mavis} = \frac{54}{3.6} = 15\ \text{m s}^{-1}$, $a_{police} = 5\ \text{m s}^{-2}$, $u_{police} = 0\ \text{m s}^{-1}$; Needed: t

Displacement of Mavis:

$v_{Mavis} = \frac{s}{t}\ \therefore 15 = \frac{s}{t}$

$s = 15t$ (1 MARK)

Displacement of police officer (s_1, t_1 whilst accelerating, s_2 and t_2 whilst at constant speed)

$s_{total} = s_1 + s_2$

$s_1 = u_{police}t_1 + \frac{1}{2}a_{police}t_1{}^2 = 0 \times 4 + \frac{1}{2} \times 5 \times 4^2 = 40\ \text{m}$ (1 MARK)

$v = u + at_1 = 0 + 5 \times 4 = 20\ \text{m s}^{-1}$

He is stationary for 10 seconds and accelerating for 4 seconds, therefore he travels at a constant speed for $t_2 = t - 14$ seconds.

$v = \frac{s_2}{t_2}\ \therefore 20 = \frac{s_2}{(t-14)}$

$s_2 = 20(t - 14) = 20t - 280$ (1 MARK)

$s_{total} = 40 + 20t - 280$

The police officer catches Mavis when their displacements are equal.

$15t = 40 + 20t - 280$ (1 MARK)

$t = 48\ \text{s}$ (1 MARK)

b $s = 15t = 15 \times 48 = 720 = 7.2 \times 10^2\ \text{m}$ (1 MARK)

11 Given: $s_{total} = 60\ \text{m}$, $t_{total} = 9.0\ \text{s}$, $t_{acceleration} = 3.0\ \text{s}$, $u = 0\ \text{m s}^{-1}$; Needed: a

Displacement, s_1, whilst accelerating:

$s_1 = ut + \frac{1}{2}at_{acceleration}{}^2 = 0 \times 3.0 + \frac{1}{2} \times a \times 3.0^2 = \frac{9}{2}a\ \text{m}$ (1 MARK)

Displacement, s_2, whilst at constant velocity:

$v = u + at_{acceleration} = 0 + a \times 3.0 = 3.0a\ \text{m s}^{-1}$ (1 MARK)

$v = \frac{s_2}{\Delta t}\ \therefore 3a = \frac{s_2}{6.0}$

$s_2 = 18a\ \text{m}$ (1 MARK)

$s_{total} = s_1 + s_2\ \therefore 60 = \frac{9}{2}a + 18a$

$a\ \text{m s}^{-2} = 2.67 = 2.7\ \text{m s}^{-2}$

The minimum acceleration Indiana Jones could have is $2.7\ \text{m s}^{-2}$. (1 MARK)

Previous lessons

12 $R_{upper} = 200 + 500 = 700\ \Omega$ (1 MARK)

$R_{lower} = \left(\frac{1}{1000} + \frac{1}{1000}\right)^{-1} + 200 = 700\ \Omega$ (1 MARK)

$R_{total} = \left(\frac{1}{R_{upper}} + \frac{1}{R_{lower}}\right)^{-1} = \left(\frac{1}{700} + \frac{1}{700}\right)^{-1} = 350\ \Omega$ (1 MARK)

This content was covered in Lesson 4E.

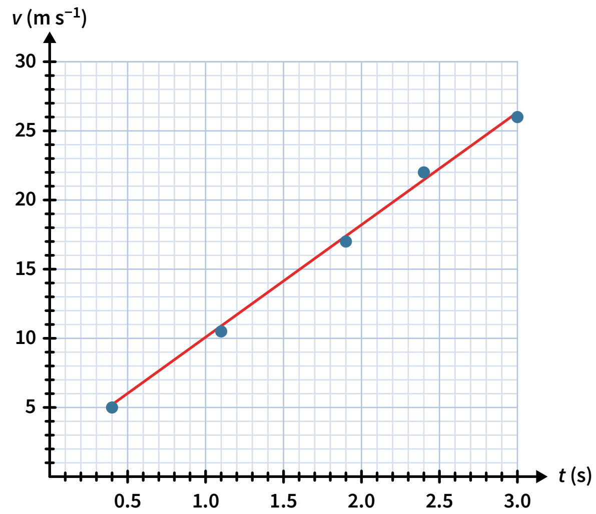
13 [The electrostatic force causes like charges to repel and unlike charges to attract one another.[1]][The strong nuclear force is an attractive force between nucleons that operates over extremely small distances.[2]][In the nucleus, when the attraction between nucleons due to the strong force is greater than the repulsion between positively charged protons due to the electrostatic force, the atom will be stable. When the strong force attraction is smaller than the electrostatic force repulsion, the atom will be radioactive.[3]]

- I have referenced the electrostatic force as being attractive between unlike charges and repulsive between like charges.[1]
- I have referenced the strong nuclear force as a force that binds nucleons together over very small distances.[2]
- I have explicitly addressed how the two forces determine whether or not the atom is stable.[3]

This content was covered in Lesson 6B.

Key science skills

14 a



- I have correctly labelled both axes and included units.
- I have used an appropriate and consistent scale so the data takes up at least half of each axis.
- I have correctly plotted each point of data.
- I have drawn a straight line of best fit.

b $gradient = \frac{rise}{run} = \frac{\Delta v}{\Delta t}$

$a = \frac{\Delta v}{\Delta t}\ \therefore gradient = a$ (1 MARK)

Using any two points on the line of best fit:

$gradient = \frac{26 - 5.0}{3.0 - 0.4} = 8.1$

$\therefore a = 8.1\ \text{m s}^{-2}$ (1 MARK)

3C

c [The theoretical (or expected) value of the acceleration is 9.8 m s^{-2}, the acceleration due to gravity.[1]][The fact that the experimental acceleration is less than the expected value is likely due to resistive forces like air resistance.[2]]

I have explicitly addressed what the expected value of the gradient would be.[1]

I have referenced the effects of resistive forces to explain the difference between the expected and calculated value of acceleration.[2]

Chapter 8 Review

Section A

1 C. Given: $u = 15$ m s^{-1}, $a = -9.8$ m s^{-2}, $v = 0$ m s^{-1}; Needed: s

$v^2 = u^2 + 2as \therefore 0^2 = 15^2 + 2 \times (-9.8) \times s$

$s = 11$ m

height = 30 + 11 = 41 m

2 C. Due to the symmetry of motion with constant acceleration, the ball will have the same speed as when it was first thrown.

3 B. The displacement-time graph is linear. This means that the gradient, which represents the velocity, is constant and so the toy car is not accelerating.

4 A. When the gradient of the velocity-time graph is positive, the acceleration will be positive. Similarly, when the gradient of the velocity-time graph is negative, the acceleration will be negative. When the velocity is constant then the acceleration will be zero.

5 B

Δs = *signed area under graph*

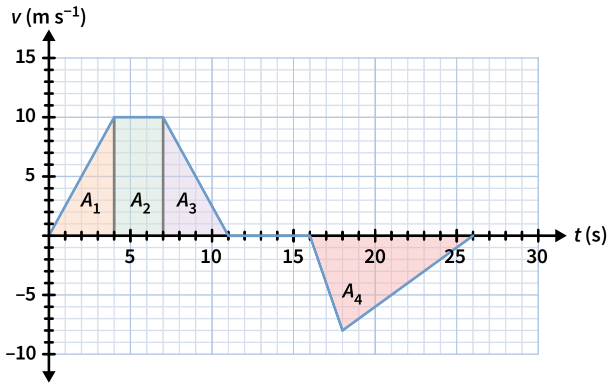
$\Delta s = \left(\frac{1}{2} \times 20 \times 6\right) + (20 \times 6) + \left(\frac{1}{2} \times 20 \times 6\right) - \left(\frac{1}{2} \times 40 \times 3\right) = 180$ m

Section B

6 **a** $a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{0 - 10}{11 - 7} = -2.5$ m s^{-2} (1 MARK)

$a = 2.5$ m s^{-2} to the east (1 MARK)

b



d = *area under graph* = $A_1 + A_2 + A_3 + A_4$

$d = \left(\frac{1}{2} \times 4 \times 10\right) + (3 \times 10) + \left(\frac{1}{2} \times 4 \times 10\right) + \left(\frac{1}{2} \times 10 \times 8\right)$ (1 MARK)

$d = 110$ m (1 MARK)

c Δs = *signed area under graph* = $A_1 + A_2 + A_3 - A_4$

$\Delta s = \left(\frac{1}{2} \times 4 \times 10\right) + (3 \times 10) + \left(\frac{1}{2} \times 4 \times 10\right) - \left(\frac{1}{2} \times 10 \times 8\right)$ (1 MARK)

$\Delta s = 30$ m to the west (1 MARK)

d $v_{avg} = \frac{\Delta s}{\Delta t} = \frac{30}{26} = 1.2$ m s^{-1} to the west (1 MARK)

7 **a** Given: $s = 300$ m, $t = 14.0$ s, $u = 0$ m s^{-1}; Needed: a

$s = ut + \frac{1}{2}at^2 \therefore 300 = 0 \times 14.0 + \frac{1}{2} \times a \times 14.0^2$ (1 MARK)

$a = 3.061 = 3.06$ m s^{-2} (1 MARK)

b As *speed* = $\frac{distance}{time}$, we must find the total distance travelled by the car during the accelerating (s_1) and decelerating (s_2) period.

total distance = $s_1 + s_2 = 300 + s_2$, need to find s_2

Accelerating period:

Given: $a = 3.061$ m s^{-2}, $t = 14.0$ s, $u = 0$ m s^{-1}; Needed: v

$v = u + at = 0 + 3.061 \times 14.0 = 42.86$ m s^{-1} (1 MARK)

Decelerating period:

Given: $u = 42.86$ m s^{-1}, $v = 0$ m s^{-1}, $t = 7.5$ s; Needed: s_2

$s_2 = \frac{1}{2}(u + v)t = \frac{1}{2}(42.86 + 0) \times 7.5 = 161$ m (1 MARK)

total distance = 300 + 161 = 461 m

speed = $\frac{distance}{time} = \frac{461}{14.0 + 7.5} = 21.4 = 21$ m s^{-1} (1 MARK)

c B (1 MARK)

The distance travelled begins at zero and increases over both the accelerating and decelerating periods. During acceleration, the gradient of the distance-time graph increases and during deceleration the gradient decreases.

d E (1 MARK)

The car accelerates and decelerates in a uniform manner, so the velocity-time graph must be linear for each section.

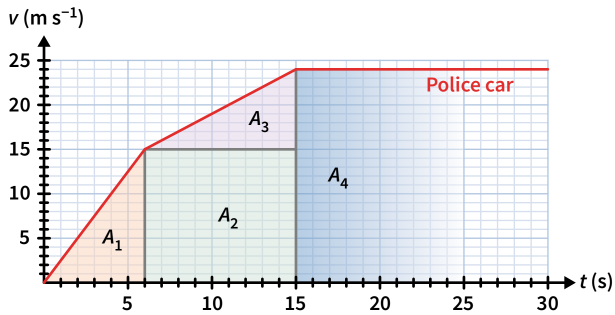
8 **a** $a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{19 - 0}{10 - 0} = 1.9$ m s^{-2} (1 MARK)

b B (1 MARK)

The acceleration decreases, indicated by the gradient decreasing, but is still positive, so the velocity will continue to increase.

c The police car will reach the motorbike when they have travelled the same distance. This is given by the area under the graph.

$s_{motorbike} = 18 \times t$ (1 MARK)



$s_{police\ car} = A_1 + A_2 + A_3 + A_4$

$s_{police\ car} = \left(\frac{1}{2} \times 6 \times 15\right) + (9 \times 15) + \left(\frac{1}{2} \times 9 \times 9\right) + 24 \times (t - 15)$ (1 MARK)

$s_{police\ car} = 220.5 + 24 \times (t - 15)$

$18 \times t = 220.5 + 24 \times (t - 15)$ (1 MARK)

$t = 23$ s (1 MARK)

9 **a** Take down as the positive direction.

For the red water balloon:

Given: $s = 20$ m, $a = 9.8$ m s^{-2}, $u = 0$ m s^{-1}; Needed: t

$s = ut + \frac{1}{2}at^2 \therefore 20 = 0 \times t + \frac{1}{2} \times 9.8 \times t^2$

$t_{red\ total} = 2.02$ s (1 MARK)

For the yellow water balloon:

Given: $s = 20$ m, $a = 9.8$ m s^{-2}, $u = 2.0$ m s^{-1}; Needed: v

$v^2 = u^2 + 2as = 2.0^2 + 2.0 \times 9.8 \times 20$

$v = 19.9$ m s^{-1} (1 MARK)

Given: $s = 20$ m, $v = 19.9$ m s^{-1}, $u = 2.0$ m s^{-1}; Needed: t

$s = \frac{1}{2}(u + v)t \therefore 20 = \frac{1}{2}(2.0 + 19.9) \times t$

$t = 1.83$ s

$t_{yellow\ total} = 1.83 + 0.50 = 2.33$ s (1 MARK)

The red water balloon will hit the ground before the yellow water balloon as 2.02 < 2.33. (1 MARK)

b E (1 MARK)

Both water balloons accelerate at the same rate, g, so their velocity-time graphs will have the same gradient. The yellow water balloon has an initial velocity of 2.0 m s^{-1} and starts after the red water balloon, so its graph will begin later.

9A Forces

Theory review questions

1 Define to the left as positive.

A-positive; B-negative; C-negative

OR

Define to the right as positive.

A-negative; B-positive; C-positive

2 C

3 gravitational field; mass; attractive; gravity

4 Demi's force should begin at *Y*. Sharni's force should begin at *U*. The force due to gravity should begin at *W*. The normal force should begin at *Z*.

5 B. Arrow length should reflect the relative magnitude of each force.

6 B

7

Force due to gravity on object by Earth	*C*
Force due to gravity on Earth by object	*D*
Normal force on table by object	*B*
Normal force on object by table	*A*

Deconstructed exam-style question

8 a C. The positive direction has been defined as to the right.

b D

c $F_{net} = F_3 + F_4 - F_1 - F_2$ (1 MARK)

$F_{net} = 80 + 200 - 150 - 150 = -20$ N (1 MARK)

$a = \frac{F_{net}}{m} = \frac{-20}{5.0} = -4.0 \text{ m s}^{-2}$ (1 MARK)

The acceleration of the rope is 4.0 m s^{-2} to the left. (1 MARK)

Exam-style questions

This lesson

9 $F_g = mg = 75.0 \times 9.8 = 735$ N

$F_g = 7.4 \times 10^2$ N (1 MARK)

10 $a = \frac{F_{net}}{m} = \frac{120}{20} = 6.0 \text{ m s}^{-2}$ (1 MARK)

11 $F_{net} = ma = 60.0 \times 7.60 = 456$ N (1 MARK)

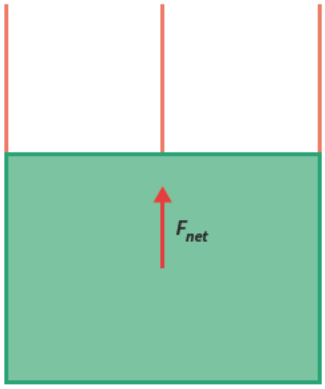
12 a Define up as the positive direction.

$F_{net} = 18 + 18 + 18 - F_g = 18 + 18 + 18 - mg$ (1 MARK)

$F_{net} = 18 + 18 + 18 - 4.6 \times 9.8 = 8.9$ N (1 MARK)

$a = \frac{F_{net}}{m} = \frac{8.9}{4.6} = 1.9 \text{ m s}^{-2}$ (1 MARK)

b



I have drawn and labelled the net force arrow.

I have drawn an arrow pointing upwards to indicate the net force direction.

I have drawn an arrow with the appropriate length to represent the relative force magnitude.

13 a Take up as the positive direction.

$F_{net} = F_N - F_g = 0 \therefore F_N = F_g$ since the box is not accelerating. (1 MARK)

$F_N = mg = 30 \times 9.8 = 294$ N

The magnitude of the normal force is 2.9×10^2 N. (1 MARK)

b $F_{net} = ma = 30 \times -9.8 = -294$ N (1 MARK)

$F_{net} = F_N - F_g \therefore -294 = F_N - 294$

$F_N = 0$ N (1 MARK)

c $F_{net} = ma = 30 \times 2.0 = 60$ N (1 MARK)

$F_{net} = F_N - F_g \therefore 60 = F_N - 294$

$F_N = 354 = 3.5 \times 10^2$ N (1 MARK)

14 [A Newton's 3rd law action-reaction pair consists of two forces that act on two different objects.[1]][The force due to gravity on the ball by the Earth and the normal force on the ball both act on the same object which means that they cannot be a Newton's 3rd law action-reaction pair.[2]]

I have used the relevant theory: Newton's 3rd law action-reaction pairs.[1]

I have explicitly addressed why the force due to gravity and the normal force are not an action-reaction pair.[2]

I have referenced Newton's 3rd law.

15 [By exerting a force on air particles to create a stream of air, a reaction force is exerted on the spacesuit by the air particles in accordance with Newton's 3rd law.[1]][This results in a net force on the suit which causes it to accelerate.[2]]

I have used the relevant theory: Newton's 3rd law.[1]

I have explicitly addressed how the spacesuit is accelerated by a stream of air.[2]

16 The object will reach maximum speed when the drag force equals the force due to gravity, since the net force will become zero and in accordance with Newton's 1st law it will no longer accelerate. (1 MARK)

$F_g = mg = 1.5 \times 9.8 = 14.7$ N (1 MARK)

From the graph, $F_{drag} = 14.7$ N at approximately 38 m s^{-1}.

Therefore the maximum speed of the object will be 38 m s^{-1}. (1 MARK)

A range of answers are acceptable for this question depending on the number read from the graph.

17 Define to the right as positive.

$F_{net} = ma = 18 \times 2.0 = 36$ N (1 MARK)

$F_{net} = F - 12 \;\; \therefore 36 = F - 12$ (1 MARK)

$F = 48$ N (1 MARK)

The required force is 48 N to the right. (1 MARKS)

Previous lessons

18 Since $I_n \propto \frac{1}{R_n}$, $I_{20\,\Omega} = \frac{1}{2} \times I_{10\,\Omega}$ (1 MARK)

$I_T = I_{10\,\Omega} + I_{20\,\Omega} = 2.50 + \frac{1}{2} \times 2.50$ (1 MARK)

$I_T = 3.75$ A (1 MARK)

This content was covered in Lesson 4D.

19 **a** $d = 3 \times 350.0 = 1050$ m (1 MARK)

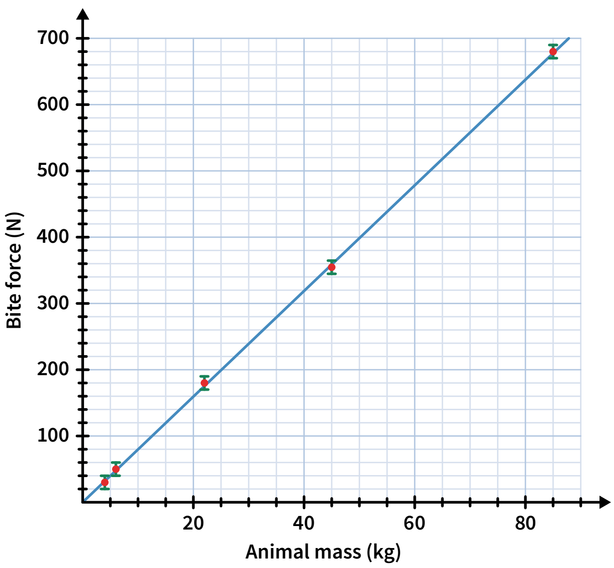
b $s = \Delta x = 0$ m (1 MARK)

c $v_{avg} = \frac{s}{t} = \frac{0}{2 \times 60} = 0$ m s^{-1} (1 MARK)

This content was covered in Lesson 8A.

Key science skills

20 **a**



I have plotted mass on the horizontal axis and force on the vertical axis.

I have included axis labels and appropriate units.

I have included an appropriate and consistent scale on the axes.

I have plotted each data point.

I have included correctly sized uncertainty bars.

I have included a line of best fit that passes through all uncertainty bars.

b The relationship between animal mass and bite force is linear and positive. (2 MARKS)

9B Force vectors in two dimensions

Theory review questions

1 A. Add the vectors using the tip-to-tail method.

2 D. As vector *Q* is acting to the left it is considered negative.

3 C. The *x*-component is the adjacent side of the force triangle and the *y*-component is the opposite side.

4 A. Use Pythagoras.

5 A. The horizontal component of the net force is the sum of the horizontal components of the original forces. Vector ***e*** will be the sum of vectors ***a*** and ***d*** despite vector ***d*** being in the negative direction.

6 C. The vertical component of the net force is the sum of the vertical components of the original forces.

7 B. Use the force triangle consisting of F_{net} and its components, ***e*** and ***f***.

Deconstructed exam-style question

8 **a** B. Transpose the force equation.

b D. The *x*-component is the adjacent side of the force triangle and the *y*-component is the opposite side.

c C

d A. The *x*-component of the sum is the sum of the *x*-components.

e B. The *y*-component of the sum is the sum of the *y*-components.

f C. Use Pythagoras.

g $F_{net} = 0 \;\; \therefore F_1 + F_2 + F_3 = 0$

$F_3 = -F_1 - F_2 = -(F_1 + F_2)$ (1 MARK)

We will find the third force by first finding $F_1 + F_2$

x-component of 30 N force: $-30 \times \cos(59°) = -15.45$ N

y-component of 30 N force: $30 \times \sin(59°) = 25.72$ N

x-component of 23 N force: $23 \times \cos(27°) = 20.49$ N

y-component of 23 N force: $-23 \times \sin(27°) = -10.44$ N (1 MARK)

Now add the components in the *x*- and *y*-directions:

$F_x = -15.45 + 20.49 = 5.04$ N (1 MARK)

$F_y = 25.72 + (-10.44) = 15.27$ N (1 MARK)

Determine the components of F_3 given $F_3 = -(F_1 + F_2)$:

x-component of $F_{3\,x} = -5.04$ N

y-component of $F_{3\,y} = -15.27$ N

Use components to determine the magnitude of the resultant force:

Magnitude of $F_3 = \sqrt{(-5.04)^2 + (-15.27)^2} = 16$ N (1 MARK)

Define the angle of the vector from the negative x-axis:

$\theta = \tan^{-1}\left(\frac{F_{3y}}{F_{3x}}\right) = \tan^{-1}\left(\frac{-15.27}{-5.04}\right) = 72°$ (1 MARK)

The third force is 16 N at 72° below the negative horizontal axis.

Exam-style questions

This lesson

9 **a** C (1 MARK)

In the x direction: $F_x = F_B - F_D = 230 - 145 = 85$ N

In the y direction: $F_y = F_A - F_C = 190 - 150 = 40$ N

Magnitude of $F_{net} = \sqrt{F_x^2 + F_y^2} = \sqrt{85^2 + 40^2} = 93.9$ N

b A (1 MARK)

$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{40}{85}\right) = 25.2°$

10

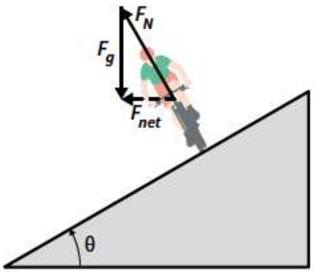
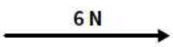


Image: Michal Sanca/Shutterstock.com

I have drawn the addition of F_N and F_g in a tip-to-tail manner.

I have draw the resultant force from the tail of F_N to the tip of F_g.

11 Taking right as the positive direction: $10 + 4 + (-8) = 6$ N



I have drawn a vector with direction to the right.

I have labelled the magnitude of the force.

12 x-component: $20 \times \cos(37°) = 16$ N (1 MARK)

y-component: $20 \times \sin(37°) = 12$ N (1 MARK)

13 **a** Take up and to the right as positive.

Find the components of the 50 N force:

$F_{50x} = 50 \times \cos(45°) = 35.36$ N (1 MARK)

$F_{50y} = -50 \times \sin(45°) = -35.36$ N (1 MARK)

Find the net force in the x- and y-directions:

$F_{net\,x} = F_{50x} + (-60) = 35.36 + (-60) = -24.64$ N (1 MARK)

$F_{net\,y} = 70 + F_{50y} = 70 + (-35.36) = 34.64$ N (1 MARK)

Magnitude of $F_{net} = \sqrt{F_{net\,x}^2 + F_{net\,y}^2}$
$= \sqrt{(-24.64)^2 + (34.64)^2} = 43$ N (1 MARK)

b $\theta = \tan^{-1}\left(\frac{F_{net\,y}}{F_{net\,x}}\right) = \tan^{-1}\left(\frac{34.64}{24.64}\right) = 55°$ (1 MARK)

14 Take to the right as positive.

As the 70 N force is acting to balance the horizontal components of the 45 N forces, we will only consider the horizontal direction.

Horizontal component of the two 45 N forces: $F_{45x} + F_{45x} = 2 \times 45 \times \cos(\theta)$ (1 MARK)

As the ball is in equilibrium $F_{net} = 0$ N

Net force in horizontal direction: $2 \times 45 \times \cos(\theta) - 70 = 0$ (1 MARK)

$\theta = 39°$ (1 MARK)

15 **a** Take up and to the right as positive.

$A_x = -70 \times \cos(27°)$

$A_y = -70 \times \sin(27°)$ (1 MARK)

$B_x = 45 \times \cos(72°)$

$B_y = 45 \times \sin(72°)$ (1 MARK)

Find the net force in the x- and y-directions.

$F_{net\,x} = A_x + B_x = (-70 \times \cos(27°)) + (45 \times \cos(72°)) = -48.46$ N (1 MARK)

$F_{net\,y} = A_y + B_y = (-70 \times \sin(27°)) + (45 \times \sin(72°)) = 11.02$ N (1 MARK)

Magnitude of $F_{net} = \sqrt{F_{net\,x}^2 + F_{net\,y}^2} = \sqrt{(-48.46)^2 + (11.02)^2}$
$= 49.70 = 50$ N (1 MARK)

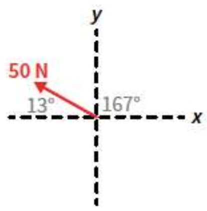
b $a = \frac{F_{net}}{m} = \frac{49.70}{5.0}$ (1 MARK)

$a = 9.9$ m s^{-2} (1 MARK)

c $\theta = \tan^{-1}\left(\frac{F_{net\,y}}{F_{net\,x}}\right) = \tan^{-1}\left(\frac{11.02}{48.46}\right) = 12.81°$ (1 MARK)

Angle with positive x-axis $= 180 - 12.81 = 167°$ (1 MARK)

d



I have drawn a vector with the correct magnitude.

I have drawn a vector with the correct angle.

Previous lessons

16 **a** Find resistance of parallel components:

$\frac{1}{R_{parallel}} = \frac{1}{R_3} + \frac{1}{R_4} = \frac{1}{20} + \frac{1}{20}$

$\frac{1}{R_{parallel}} = \frac{2}{20}$ $\therefore R_{parallel} = 10\ \Omega$ (1 MARK)

Find the resistance of the whole circuit:

$R_T = R_1 + R_2 + R_{parallel} = 10 + 15 + 10 = 35\ \Omega$ (1 MARK)

b $V_T = I_T R_T \therefore 7.0 = I_T \times 35$

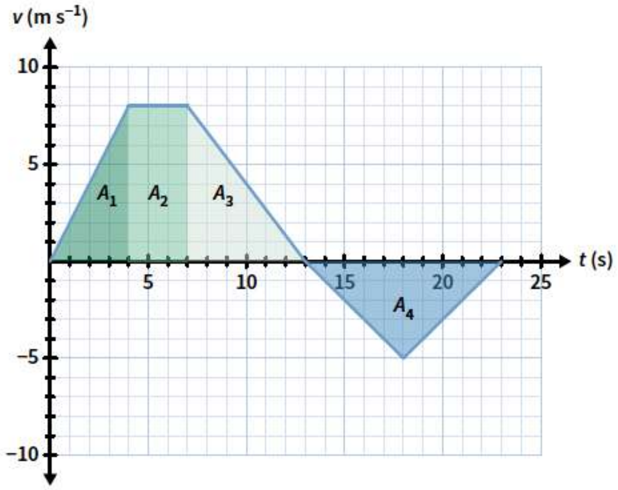
$I_T = 0.20$ A (1 MARK)

This content was covered in Lesson 4E.

17 **a** a_{avg} = gradient of velocity vs time graph

$a_{avg} = \frac{rise}{run} = \frac{8-0}{4-0} = 2 \text{ m s}^{-2}$ (1 MARK)

b



$\Delta s = \text{area under graph} = A_1 + A_2 + A_3 - A_4$ (1 MARK)

$\Delta s = \left(\frac{1}{2} \times 4 \times 8\right) + (3 \times 8) + \left(\frac{1}{2} \times 6 \times 8\right) - \left(\frac{1}{2} \times 10 \times 5\right) = 39 \text{ m}$ (1 MARK)

Therefore Ken finishes 39 m from where he started. (1 MARK)

This content was covered in Lesson 8B.

Key science skills

18 [Forcia has more accurate data and Victor has more precise data.[1]] [Forcia's average (5.51 N) is closer than Victor's average (5.43 N) to the actual force (5.50 N), so her data is more accurate.[2]] [The range of Victor's measurements (0.04 N) is smaller than Forcia's range (0.22 N), so his data is more precise.[3]]

- I have explicitly addressed who is more accurate and who is more precise.[1]
- I have used the relevant theory: the definition of accuracy.[2]
- I have used the relevant theory: the definition of precision.[3]
- I have used the provided data in my answer.

9C Inclined planes and connected bodies

Theory review questions

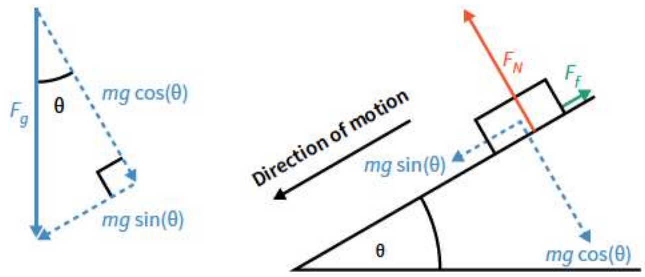
1 E. The force due to gravity acts vertically downwards.

2 H. The normal force acts perpendicular to the plane.

3 B. The friction force acts opposite to the direction of motion.

4 $F_{net} = H + E + B$. The net force is equal to the addition of all the forces acting on the block; normal force (H), force due to gravity (E) and the friction force (B).

5 F. The component of the force due to gravity which acts parallel to the plane acts down the plane.



6 B. The component of the force due to gravity that acts down the slope is given by $F_{ds} = mg\sin(\theta)$. The friction force, F_f, must be subtracted as it acts down the slope. The normal force cancels out with the component of the force due to gravity that acts perpendicular to the plane, so it can be ignored when finding the net force.

7 **a** whole combined; cancels out

b individual block or cart; is acting on the block and cart

8 the same; up the slope

9 C. As both objects are accelerating at the same rate and the truck has twice the mass of the car, the net force on the truck must be twice as much as the net force on the car.

10 greater than; same; equal to; opposite

Deconstructed exam-style question

11 **a** A. $F_{net\ truck} = m_{truck}a = 5.0 \times 10^3 \times 5.0 \times 10^{-2} = 2.5 \times 10^2 \text{ N}$

b B

c B. $F_{net} = m_{total}a = (5.0 \times 10^3 + 2.0 \times 10^3) \times 5.0 \times 10^{-2} = 3.5 \times 10^2 \text{ N}$

d D

e Consider the truck when finding tension, T.

$F_{net\ truck} = m_{truck}a = 5.0 \times 10^3 \times 5.0 \times 10^{-2} = 2.5 \times 10^2 \text{ N}$

$F_{net\ truck} = 1000 - T \therefore 2.5 \times 10^2 = 1000 - T$ (1 MARK)

$T = 7.5 \times 10^2 \text{ N}$ (1 MARK)

Consider the whole system when finding the driving force, F_x.

$F_{net} = m_{total}a = (5.0 \times 10^3 + 2.0 \times 10^3) \times 5.0 \times 10^{-2} = 3.5 \times 10^2$ (1 MARK)

$F_{net} = 1000 - F_x \therefore 3.5 \times 10^2 = 1000 - F_x$ (1 MARK)

$F_x = 6.5 \times 10^2 \text{ N}$ (1 MARK)

Exam-style questions

This lesson

12 **a** Force due to gravity, F_g (1 MARK)

Normal force, F_N (1 MARK)

b $F_{ds} = mg\sin(\theta) = 20 \times 9.8 \times \sin(30°)$ (1 MARK)

$F_{ds} = 98 \text{ N}$ (1 MARK)

c $F_N = mg\cos(\theta) = 20 \times 9.8 \times \cos(30°)$ (1 MARK)

$F_N = 170 = 1.7 \times 10^2 \text{ N}$ (1 MARK)

13 a Combined system

$\therefore F_{net} = F_d = (m_A + m_B) \times a = (2500 + 1000) \times 2.0$ (1 MARK)

$F_d = 7000 = 7.0 \times 10^3$ N (1 MARK)

b Boat system $F_{net} = T = m_B \times a = 1000 \times 2.0$ (1 MARK)

$T = 2000 = 2.0 \times 10^3$ N (1 MARK)

14 a As we do not know the value of the contact force on block *B*, we will consider the combined system.

$F_{net} = (m_A + m_B) \times a = 70$ N

$(3.0 + 5.0) \times a = 70$ (1 MARK)

$a = 8.75 = 8.8$ m s^{-2} (1 MARK)

b As the force on block *B* by block *A* is the only force on block *B*, we will consider its individual system.

$F_{net\,B} = F_{on\,B\,by\,A} = m_B \times a$

$F_{on\,B\,by\,A} = 5.0 \times 8.75 = 43.8 = 44$ N (1 MARK)

c $F_{on\,A\,by\,B} = 44$ N (1 MARK)

$F_{on\,A\,by\,B}$ is to the left by Newton's third law. (1 MARK)

15 a

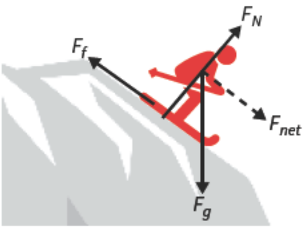


Image: VectorShow/Shutterstock.com

- I have drawn the force due to gravity vector straight down from the centre of mass.
- I have drawn the normal force vector perpendicular to the inclined plane from the point of contact.
- I have drawn the friction force vector acting up the inclined plane from the point of contact.
- I have drawn the net force vector as a dotted line acting down the inclined plane from the centre of mass.
- I have drawn the force vectors to an appropriate size.
- I have correctly labelled each force.

b $F_{net} = F_{ds} - F_f = mg\sin(\theta) - F_f$ (1 MARK)

$F_{net} = 80 \times 9.8 \times \sin(15°) - 75 = 128 = 1.3 \times 10^2$ N (1 MARK)

c $F_{net} = ma \;\therefore 128 = 80 \times a$

$a = 1.6$ m s^{-2} (1 MARK)

16 Take left as the positive direction.

a Combined system: a = 0 $\therefore F_{net} = 0$ (1 MARK)

$F_{net} = F_d - 800 - 300 = 0$

$F_d = 1100 =t1.10 \times 10^3$ N (1 MARK)

b Car system: $a = 0 \;\therefore F_{net} = 0$

$F_{net} = T - 300 = 0$

$T = 300$ N (1 MARK)

c Car system: $F_{net} = T - F_f = ma$

$F_{net} = T - 300 = 1500 \times 2.0$ (1 MARK)

$T = 3300 = 3.3 \times 10^3$ N (1 MARK)

d [The tension force acting on the bus will be equal in magnitude but opposite in direction to the tension acting on the car.[1]] [Hence, the tension force will be 3.3×10^3 N acting to the right.[2]]

- I have used the relevant theory: Newton's third law.[1]
- I have specifically addressed the magnitude and direction of the tension force.[2]

17 a 0 N. As the shopping cart is moving at a constant speed down the hill, the net force acting on it is zero.

b $F_N = mg\cos(\theta) = 70.0 \times 9.8 \times \cos(10.0°)$ (1 MARK)

$F_N = 676 = 6.8 \times 10^2$ N (1 MARK)

The normal force acts perpendicular to the hill. (1 MARK)

c $F_{ds} = mg\sin(\theta) = 70.0 \times 9.8 \times \sin(10.0°)$ (1 MARK)

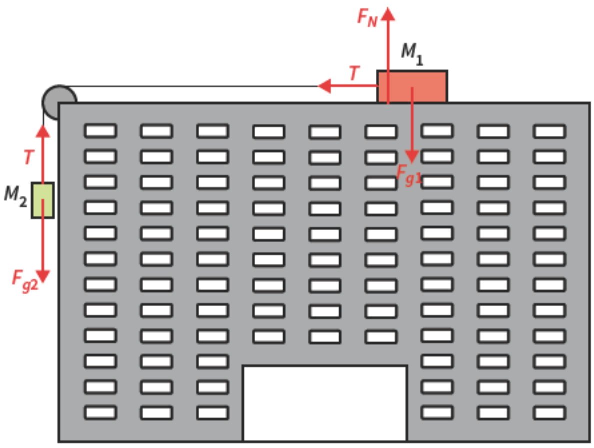
$F_{ds} = 119 = 1.2 \times 10^2$ N (1 MARK)

d The car is not accelerating $\therefore F_{net} = 0$ N

$F_{net} = F_{ds} - F_f \;\therefore 0 = 119 - F_f$ (1 MARK)

$F_f = 119 = 1.2 \times 10^2$ N (1 MARK)

18 a



- I have drawn a force due to gravity vector acting vertically down from the centre of each box.
- I have drawn a tension force vector acting along the string from both boxes.
- I have drawn the normal force vector acting vertically up from the point of contact of box one.
- I have correctly labelled each force.

b Combined system: $F_{net} = F_{g2} = m_2 g = 60.0 \times 9.8 = 588$ N (1 MARK)

$F_{net} = (m_1 + m_2) \times a$

$588 = (85.0 + 60.0) \times a$ (1 MARK)

$a = 4.06 = 4.1$ m s^{-2} (1 MARK)

c M_1 system: $F_{net\,M1} = m_1 a = T$

$T = 85 \times 4.06 = 344.7 = 3.4 \times 10^2$ N (1 MARK)

d Combined system: $F_{net} = F_{g2} - F_f = m_2 g - F_f$

$F_{net} = (m_1 + m_2) \times a$

$m_2 g - F_f = (m_1 + m_2) \times a$ (1 MARK)

$60.0 \times 9.8 - F_f = (85.0 + 60.00) \times 1.0$ (1 MARK)

$F_f = 443 = 4.4 \times 10^2$ N (1 MARK)

Previous lessons

19 **a** $V = IR = 2.0 \times 3.0 = 6.0$ V

b The voltage drop across R_2 and R_3 will be the same as they are components in parallel.

$V = IR$ ∴ $6.0 = I \times 2.0$ (1 MARK)

$I = \frac{6.0}{2.0} = 3.0$ A (1 MARK)

c The current through R_1 will be the addition of the current through R_2 and R_3.

$I = 3.0 + 2.0 = 5.0$ A (1 MARK)

The voltage drop across R_1 will be the difference between the battery voltage and voltage drop across the parallel components.

$V = 12 - 6.0 = 6.0$ V (1 MARK)

$V = IR$ ∴ $6.0 = 5.0 \times R_1$

$R_1 = 1.2\ \Omega$ (1 MARK)

This content was covered in Lesson 4E.

20 **a** $v = u + at = 0 + 7.0 \times 5.0$ (1 MARK)

$v = 35$ m s^{-1} (1 MARK)

b $v^2 = u^2 + 2as$ (1 MARK)

$0^2 = 35^2 + 2 \times (-10) \times s$

$s = 61.3 = 61$ m (1 MARK)

Hence, the BMW will stop before making contact with the elephant 75 m away. (1 MARK)

This content was covered in Lesson 8C.

Key science skills

21 **a** uncertainty $= \frac{1}{2} \times$ smallest gradation on scale $= \frac{1}{2} \times 0.2$

uncertainty = 0.1 seconds (1 MARK)

b The consistent delay of 0.6 seconds in the stopwatch is a systematic error. (1 MARK)

It could be reduced by using a more accurate measurement device such as a digital stopwatch. (1 MARK)

9D Torque

Theory review questions

1 D. Torque will be at a minimum when the force acts parallel to the door.

2 B. Torque will be at a maximum when the force acts perpendicular to the door.

3 the same as

4 greater than

5 C. The value of $\sin(\theta_1)$ and $\sin(\theta_2)$ are the same, so either angle can be used.

6 II; IV. Torque must be equivalent to $\tau = r_\perp F = 20 \times 10^{-2} \times 10 = 2.0$ N m.

7 B. A greater torque does not necessarily cause a car to accelerate faster, it refers to the rotational force in the engine.

8 a downwards; an anticlockwise
an upwards; a clockwise

Deconstructed exam-style questions

9 **a** A. $F_g = mg = 77 \times 9.8$

b C. $\tau_1 = r_\perp F = r \times F_g$ clockwise

c B. $\tau_2 = r_\perp F = rF\sin(\theta) = r \times F_g \times \sin(60°)$ anticlockwise

d B. $\tau_{net} = \tau_2 - \tau_1 = r \times F_g \times \sin(60°) - r \times F_g$

e Consider the force due to gravity from each friend:

$F_g = mg = 77 \times 9.8 = 754.6$ N (1 MARK)

Consider the two torques acting on the Ferris wheel:

$\tau_1 = r_\perp F = r \times 754.6$ clockwise (1 MARK)

$\tau_2 = rF\sin(\theta) = r \times 754.6 \times \sin(60°)$ anticlockwise (1 MARK)

Consider the net torque acting on the Ferris wheel due to τ_1 and τ_2:

$\tau_{net} = \tau_2 - \tau_1 = r \times 754.6 \times \sin(60°) - r \times 754.6$

$805 = r \times 754.6 \times \sin(60°) - r \times 754.6$ (1 MARK)

$r = 7.96 = 8.0$ m (1 MARK)

Exam-style questions

This lesson

10 **a** $\tau = r_\perp F = 25.0 \times 10^{-2} \times 125$ (1 MARK)

$\tau = 31.25 = 31.3$ N m (1 MARK)

b $\tau = r_\perp F$ ∴ $31.25 = 35.0 \times 10^{-2} \times F$ (1 MARK)

$F = 89.29 = 89.3$ N (1 MARK)

11 $\tau = r_\perp F$ ∴ $1200 = r_\perp \times 900$ (1 MARK)

$r_\perp = 1.33$ m (1 MARK)

12 [When the force is directed towards the axis of rotation in direction *A*, it is parallel to the object and the torque will be zero.[1]][As the force rotates towards the perpendicular direction, the torque will increase until it is at a maximum (when the force acts perpendicular to the line between the pivot point and the point where the force is applied, in direction *C*).[2]][The torque will then decrease until the force acts away from the axis of rotation in direction *E*: here it is parallel to the object and the torque will be zero.[3]]

- I have explicitly addressed the torque when the force acts in direction *A*.[1]
- I have explicitly addressed the torque as the force changes to act in direction *C*.[2]
- I have explicitly addressed the torque as the force changes to act in direction *E*.[3]

13 **a** $\tau = rF\sin(\theta) = 85 \times 10^{-2} \times 25 \times \sin(120°)$ (1 MARK)

$\tau = 18.4 = 18$ N m in the anticlockwise direction (2 MARKS)

b [If the force on the umbrella was increased by a factor of 2, the torque will also increase by a factor of 2.[1]][This is because torque is directly proportional to the force as seen in the equation $\tau = r_{\perp}F$.[2]]

- I have explicitly addressed the factor by which torque increases.[1]
- I have used the relevant theory: torque is directly proportional to force.[2]

c [For the maximum torque to act on the umbrella, the force should be directed perpendicular to the handle of the umbrella.[1]][This is because torque is proportional to the sine of the angle between the force and the line between the pivot point and the point of application of the force, as seen in the equation $\tau = rF\sin(\theta)$,[2]][and this has a maximum value of 1 at 90°.[3]]

- I have explicitly addressed the direction of force which will cause the maximum torque.[1]
- I have used the relevant theory: torque with non-perpendicular forces.[2]
- I have used the relevant theory: torque is at a maximum when perpendicular.[3]

14 $F_g = mg = 500 \times 9.8 = 4.90 \times 10^3$ N (1 MARK)

4.0 m is the lever arm $r_{\perp}$

$\tau = r_{\perp}F_g = 4.0 \times 4.9 \times 10^3$ (1 MARK)

$\tau = 1.96 \times 10^4 = 2.0 \times 10^4$ N m in the anticlockwise direction (1 MARK)

OR

$F_g = mg = 500 \times 9.8 = 4.90 \times 10^3$ N (1 MARK)

$\sin(\theta) = \dfrac{opposite}{hypotenuse} = \dfrac{4.0}{5.0} = 0.80$

$\tau = rF_g\sin(\theta) = 5.0 \times 4.90 \times 10^3 \times 0.80$ (1 MARK)

$\tau = 1.96 \times 10^4 = 2.0 \times 10^4$ N m in the anticlockwise direction (1 MARK)

15 **a** Take the anticlockwise direction as positive.

$\tau_{net} = \tau_{150} - \tau_{50} = rF\sin(\theta) - r_{\perp}F$ (1 MARK)

$\tau_{net} = 0.90 \times 150 \times \sin(70°) - 0.60 \times 50$ (1 MARK)

$\tau_{net} = 96.9 = 97$ N m in the anticlockwise direction (2 MARKS)

b Take the anticlockwise direction as positive.

$\tau_{net} = \tau_{150} - \tau_{50} = rF\sin(\theta) - r_{\perp}F$ (1 MARK)

$100 = 0.90 \times 150 \times \sin(\theta) - 0.60 \times 50$ (1 MARK)

$\theta = 74.4 = 74°$ (1 MARK)

Previous lessons

16 **a** [The function of a residual-current device is to stop the flow of electrical current in dangerous situations.[1]][The device operates by measuring the current in the live and neutral wires: when a difference is detected between the two wires (indicating that a fault has occurred)[2]][the electrical circuit is broken for the safety of those nearby.[3]]

- I have explicitly addressed the function of a residual-current device.[1]
- I have used the relevant theory: operation of a residual-current device.[2]
- I have related my answer to the context of the question.[3]

b When a person cuts a power cord with an electrical tool, such as a hedge trimmer. (1 MARK)

A faulty kitchen appliance that shorts the live wire to earth (electrically connected to the earth). (1 MARK)

Note that a variety of answers are acceptable for this question.

This content was covered in Lesson 5C.

17 **a** $F_g = mg = 2.0 \times 10^{-6} \times 9.8$

$F_g = 1.96 \times 10^{-5} = 2.0 \times 10^{-5}$ N downwards (2 MARKS)

b

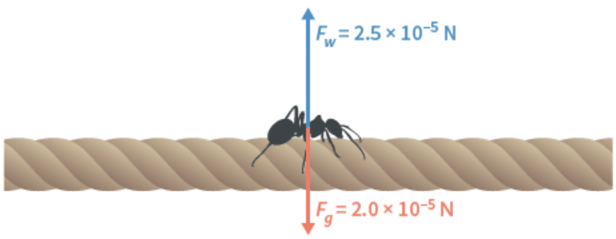


Image: designer_an/Shutterstock.com

- I have drawn the force due to gravity, F_g, acting vertically downwards and originating at the centre of the ant.
- I have drawn the force due to the wind, F_w, acting vertically upwards.
- I have drawn the force due to gravity slightly smaller than the force due to the wind.
- I have correctly labelled the force due to gravity and force due to the wind vectors.

c Take up as positive:

$F_{net} = F_w - F_g = 2.5 \times 10^{-5} - 1.96 \times 10^{-5}$

$F_{net} = 5.4 \times 10^{-6}$ N (1 MARK)

$F_{net} = ma \therefore 5.4 \times 10^{-6} = 2.0 \times 10^{-6} \times a$ (1 MARK)

$a = 2.7$ m s^{-2} (1 MARK)

This content was covered in Lesson 9A.

Key science skills

18 a Independent variable: force applied to bottle opener (1 MARK)

Dependent variable: torque on bottle cap (1 MARK)

Controlled variable: the angle at which the force is applied **OR** the bottle opener used **OR** the bottle used (1 MARK)

b Susie could use a more precise torque sensor. (1 MARK)

c Susie could take multiple measurements for each level of force applied, and calculate an average value. (1 MARK)

9E Equilibrium

Theory review questions

1 B. No. As there is only one equation we can simply use the translational equilibrium equation in one direction.

2 A. Yes. As there is more than one unknown we require the use of the rotational equilibrium equation.

3 A. Yes. As there is more than one unknown we require the use of the rotational equilibrium equation.

4 A. Calculating torques around point A means that T_{rope} is eliminated from the rotational equilibrium equation so that F_B is the only unknown quantity.

5 A, B, C, D, E. If a system is in equilibrium, the net torque is zero around all points.

6 B

7 B

Deconstructed exam-style question

8 a A. The force from the suspended mass is directed vertically downwards with a magnitude of 45*g* N. The perpendicular (horizontal) distance from point *I* to the line of action (*FE*) is 2.5 m.

b A. The tension force acts perpendicularly to the beam. The distance from point *I* to point *G* is 3.5 m.

c A. The force due to gravity on the beam is directed vertically downwards with a magnitude of 10*g*. We treat it as acting halfway along the length of the beam, so the perpendicular (horizontal) distance from point *I* to the line of action is half the horizontal length of the beam ($\frac{2.5}{2} = 1.25$ m).

d Around point *I*: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore \tau_{GH} = \tau_{FE} + \tau_{g\,beam}$

$r_G T_{GH} = r_{F\perp} F_{FE} + r_{centre\perp} F_{g\,beam}$ (1 MARK)

$3.5 \times T_{GH} = 2.5 \times 45 \times 9.8 + \frac{2.5}{2} \times 10 \times 9.8$ (1 MARK)

$T_{GH} = 350$ N (1 MARK)

Exam-style questions

This lesson

9 a Translational equilibrium: $\Sigma F = 0 \therefore F_1 + F_2 = F_{g\,slab}$

$F_{g\,slab} = mg = 40.0 \times 10^3 \times 9.8 = 392\,000$ N (1 MARK)

$F_{1st\,pillar} = F_{2nd\,pillar} = \frac{1}{2} \times 3.92 \times 10^5 = 1.96 \times 10^5$ N (1 MARK)

b Around pillar 1: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore r_{centre} F_{g\,slab} + r_{truck} F_{truck} = r F_2$

$20 \times 40.0 \times 10^3 \times 9.8 + 30 \times 6.0 \times 10^3 \times 9.8 = 40.0 \times F_2$ (1 MARK)

$F_2 = 240\,100 = 2.4 \times 10^5$ N (1 MARK)

Translational equilibrium: $\Sigma F = 0 \therefore F_1 + F_2 = F_{g\,slab} + F_{truck}$

$F_1 + 240\,100 = 40.0 \times 10^3 \times 9.8 + 6.0 \times 10^3 \times 9.8$ (1 MARK)

$F_1 = 210\,700 = 2.1 \times 10^5$ N (1 MARK)

10 a Around the centre: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore r \times F_{55\,kg} = d \times F_{70\,kg}$ (1 MARK)

$2.5 \times 55 \times 9.8 = d \times 70 \times 9.8$ (1 MARK)

$d = 1.96 = 2.0$ m (1 MARK)

b $F_N = F_{55\,kg} + F_{70\,kg} = 55 \times 9.8 + 70 \times 9.8$ (1 MARK)

$F_N = 1225 = 1.2 \times 10^3$ N (1 MARK)

11 Around *Y*: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore r_x F_x = r_{centre} F_g$

$12.0 \times F_x = 3.0 \times 2000 \times 9.8$ (1 MARK)

$F_x = 4900$ N (1 MARK)

12 Around B: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore r_{man} \times F_{man} + r_{centre} \times F_{bench} = r_C \times F_C$

$1.5 \times 75 \times 9.8 + 0.5 \times 60 \times 9.8 = 1.0 \times F_C$

$F_C = 1396.5 = 1.4 \times 10^3$ N (1 MARK)

13 a D. The system is in equilibrium.

b Around *E*: $\Sigma\tau_{clockwise} = \Sigma\tau_{anticlockwise} \therefore \tau_G = \tau_H$

$r_G F_{G\,y} = r_H F_H \therefore 0.15 \times F_{G\,y} = 0.55 \times 30 \times 9.8$

$F_{G\,y} = 1078$ N (1 MARK)

Calculate the horizontal component of the force.

$F_{G\,y} = F_{G\,x} \tan(\theta) \therefore 1078 = F_{G\,x} \times \tan(50°)$ (1 MARK)

$F_{G\,x} = 904.5$ N

$\Sigma F = 0 \therefore F_{E\,x} - F_{G\,x} = 0 \therefore F_{E\,x} = 904.5 = 9.0 \times 10^2$ N (1 MARK)

14 About the fulcrum: $\Sigma\tau_{cw} = \Sigma\tau_{acw} \therefore \tau_p = \tau_{block}$

$0.30 \times F_p = 2.0 \times 20 \times 9.8$ (1 MARK)

$F_p = 1.3 \times 10^3$ N (1 MARK)

Previous lessons

15 $V_{LED} = 2.0$ V

$P = VI \therefore 0.35 = 2.0 \times I \therefore I = 0.175$ A (1 MARK)

$V = IR \therefore 8.0 = 0.175 \times R$ (1 MARK)

$R = 46\ \Omega$ (1 MARK)

This content was covered in Lesson 5A.

16 a Team A Team B

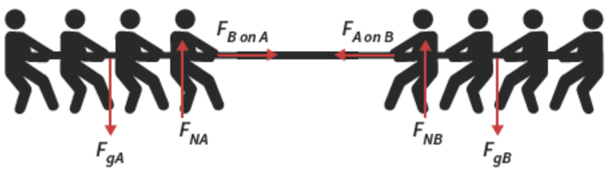


Image: Miceking/Shutterstock.com

- I have included forces for both team A on B and team B on A.
- I have included force due to gravity for both teams.
- I have included arrows with appropriate direction.
- I have included arrows with appropriate labels.

b $F_{net} = F_{B\ on\ A} - F_{A\ on\ B}$ $\therefore F_{net} = 4020 - 4000 = 20$ N (1 MARK)

$F_{net} = ma$ $\therefore 20 = (300 + 305) \times a$

$a = 3.3 \times 10^{-2}$ m s^{-2} to the right (1 MARK)

This content was covered in Lesson 9A.

Key science skills

17 [The type of error is systematic error[1]][because it affects all results equally.[2]]

- I have explicitly addressed the type of error.[1]
- I have used the relevant theory: the definition of systematic error.[2]

Chapter 9 Review

Section A

1 C. Find the resultant force in the horizontal direction then solve using Pythagoras: $F = \sqrt{21^2 + (32.9 - 23.8)^2} = 23$ N

2 A. $a = \frac{F_{net}}{m} = \frac{2.54 \times 10^4}{1.20 \times 10^3} = 21.2$ m s^{-2}

3 A. $\tau = rF_g \sin(\theta) = 1.3 \times 70 \times 9.8 \times \sin(90° - 20°) = 838$ N m

4 C. $F_{on\ A\ by\ B} = m_A g = 7.0 \times 9.8 = 68.6 = 69$ N. Brick *B* pushes upwards on brick *A*.

5 D

Force due to gravity on *PR* acts 5.0 m from *P*.

Around point *P*, $\Sigma\tau_{clockwise} = \Sigma\tau_{anticlockwise}$ $\therefore 5.0 \times 3000 \times 9.8 = 3.0 \times F_{QS}$

$F_{QS} = 49\,000$ N

Section B

6 a $F_g = mg = 30 \times 9.8 = 294 = 2.9 \times 10^2$ N down (1 MARK)

b Since cart is not accelerating in vertical direction:

$F_N = F_g = 2.9 \times 10^2$ N (1 MARK)

c Define to the right as the positive direction.

$F_{net} = ma$ $\therefore 450 - 400 = 30 \times a$ (1 MARK)

$a = 1.7$ m s^{-2} to the right (1 MARK)

7 $\tau_A = r_A F_A \sin(\theta) = 0.225 \times 1000 \times \sin(60°) = 194.9$ N m (1 MARK)

$\tau_B = r_B F_B = 0.45 \times F_B$

$\tau_A = \tau_B$ $\therefore 194.9 = 0.45 \times F_B$ (1 MARK)

$F_B = 4.3 \times 10^2$ N (1 MARK)

8 [Newton's first law of motion states that an object in motion continues moving with the same velocity unless acted upon by a net external force.[1]] [As the bike is initially in motion but does not remain in motion, there must be an external force slowing the bike down.[2]]

- I have referenced Newton's first law of motion correctly.[1]
- I have explicitly addressed why there must be a force acting.[2]

9 $F_{net} = ma = mg\sin\theta - F_f$ $\therefore m \times 0.500 = m \times 9.8 \times \sin(28.0°) - 320$ (1 MARK)

$m = 78.0$ kg (1 MARK)

$F_N = mg\cos\theta = 78.0 \times 9.8 \times \cos(28.0°) = 675$ N (1 MARK)

10 a As $F_{net} = 0$, $T_2 = 75 + 75$ N

$T_2 = 150$ N (1 MARK)

b Consider the left-hand storage unit:

$m_1 a = T_1 - 75$ $\therefore 15 \times 0.30 = T_1 - 75$ (1 MARK)

$T_1 = 79.5 = 80$ N (1 MARK)

c Consider both storage units as a single system:

$m_{total} a = T_2 - 150$ $\therefore 30 \times 0.30 = T_2 - 150$ (1 MARK)

$T_2 = 159$ N (1 MARK)

11 The sum of the vertical components of the tensions in each rope must balance the force due to gravity on the plant: $T_{1\ up} + T_{2\ up} = F_g$

$T_{1\ up} = T_{2\ up}$ due to the symmetry of the ropes.

$T_{1\ up} = \frac{1}{2} \times F_g = \frac{1}{2} \times 8.0 \times 9.8 = 39.2$ N (1 MARK)

$T_1 \sin(\theta) = T_{1\ up}$ $\therefore T_1 \sin(55°) = 39.2$ N

$T_1 = T_2 = 48$ N (1 MARK)

12 a Around point *E*, $\Sigma\tau_{anticlockwise} = \Sigma\tau_{clockwise}$

$r_{EG} T_{FG\perp} = r_{beam} F_{g\ beam} + r_{EH} F_{g\ mass}$

$0.50 \times T_{FG\perp} = 1.0 \times 20 \times 9.8 + 2.0 \times 250 \times 9.8$ (1 MARK)

$T_{FG\perp} = 10\,192$ N (1 MARK)

$T_{FG\perp} = T_{FG} \sin(45°)$ $\therefore 10\,192 = T_{FG} \sin(45°)$

$T_{FG} = 14\,414 = 1.4 \times 10^4$ N (1 MARK)

b $T_{max} = 20\,000$ $\therefore T_{max\perp} = 20\,000 \times \sin(45°)$

$T_{max\perp} = 14\,142$ N (1 MARK)

Around point *E*, $\Sigma\tau_{anticlockwise} = \Sigma\tau_{clockwise}$

$r_{EG} T_{max\perp} = r_{007} F_{g\ 007} + r_{beam} F_{g\ beam} + r_{EH} F_{g\ mass}$

$0.5 \times 14\,142 = 1.25 \times m \times 9.8 + 1.0 \times 20 \times 9.8 + 2.0 \times 250 \times 9.8$ (1 MARK)

$m = 161 = 1.6 \times 10^2$ kg (1 MARK)

10A Momentum and impulse

Theory review questions

1 vector; velocity; same; a net force acting on

2 the same as

3 the same as

4 less than

5 C. As car X has a greater initial and final velocity than car Y, its momentum is larger than the momentum of car Y at both points. As both cars have the same mass and increase their velocity by the same amount, then the change in momentum and impulse will be equal.

6 equal; left

7 C. The change in momentum of the bowling ball will have the same magnitude but opposite direction to the impulse given to the soccer ball. Hence it will have a magnitude of 10 kg m s^{-1} and act to the left.

8 B. Before the collision, the velocity of block A is positive and the velocity of block B is negative. After the collision, both blocks are moving to the left so they have a negative velocity.

Deconstructed exam-style question

9 **a** D **b** A **c** D

d C **e** B

f $\Sigma p_i = p_A + p_B = m_A u_A + m_B u_B = 2.0 \times 10 + 5.0 \times 0 = 20$ kg m s^{-1} or N s to the right (1 MARK)

By the law of conservation of momentum, $\Sigma p_i = \Sigma p_f$.

$\Sigma p_f = 20$ kg m s^{-1} or N s to the right

Find velocity of the blocks after the collision.

$\Sigma p_f = m_{total} v = (m_A + m_B) \times v \;\therefore 20 = (2.0 + 5.0) \times v$ (1 MARK)

$v = 2.86 = 2.9$ m s^{-1} (1 MARK)

The impulse given to block B is the same as its change in momentum.

$I_B = \Delta p_B = m_B \Delta v = m_B \times (v - u_B)$

$I_B = 5.0 \times (2.86 - 0) = 14.3 = 14$ kg m s^{-1} or N s to the right (1 MARK)

$I = F_{avg} \Delta t \;\therefore 14.3 = F_{avg} \times 4.0 \times 10^{-2}$ (1 MARK)

$F_{avg} = 357 = 3.6 \times 10^2$ N (1 MARK)

Exam-style questions

This lesson

10 $p = mv = 3.5 \times 10 = 35$ kg m s^{-1} or N s to the south (2 MARKS)

11 **a** $\Sigma p_i = p_{car} + p_{F1} = m_{car} u_{car} + m_{F1} u_{F1}$

$\Sigma p_i = 1900 \times 20 + 750 \times (-80) = -2.2 \times 10^4$ kg m s^{-1} or N s (1 MARK)

$\Sigma p_i = 2.2 \times 10^4$ kg m s^{-1} or N s to the left (1 MARK)

b $\Sigma p_f = \Sigma p_i = -2.2 \times 10^4$ kg m s^{-1} or N s

$\Sigma p_f = mv = (m_{car} + m_{F1}) \times v$

$-2.2 \times 10^4 = (1900 + 750) \times v$ (1 MARK)

$v = -8.30$ m s^{-1}

$v = 8.30$ m s^{-1} to the left (1 MARK)

12 **a** $I = \Delta p = m\Delta v = 10\,000 \times (0 - 25) = -2.5 \times 10^5$ (1 MARK)

$I = 2.5 \times 10^5$ kg m s^{-1}

b $I = F_{avg} \Delta t \;\therefore 2.5 \times 10^5 = 12\,500 \times \Delta t$ (1 MARK)

$\Delta t = 20$ s (1 MARK)

c $p_i = mu = 10\,000 \times 25 = 2.5 \times 10^5$ kg m s^{-1} or N s (1 MARK)

$p_f = mv = 10\,000 \times 0 = 0$ kg m s^{-1} or N s (1 MARK)

d [Momentum is conserved in this situation[1]][when the isolated system includes the truck and the earth.[2]][The impulse given to the truck by the earth is equal and opposite to the impulse given to the earth by the truck, and hence momentum is conserved.[3]]

- I have explicitly addressed whether momentum is conserved.[1]
- I have referenced the isolated system in this situation.[2]
- I have used the relevant theory: the law of conservation of momentum.[3]

13 **a** Take the right as positive:

$I = \Delta p = m_{ball} \Delta v = 0.050 \times (62 - (-30)) = 4.6$ (1 MARK)

$I = 4.6$ kg m s^{-1} or N s (1 MARK)

b The impulse on the tennis racket will be equal in magnitude but opposite in direction to the impulse on the tennis ball. $I_{racket} = -I_{ball}$

$I_{racket} = 4.6$ kg m s^{-1} or N s to the left (2 MARKS)

c $I = F_{avg} \Delta t \;\therefore 4.6 = 230 \times \Delta t$ (1 MARK)

$\Delta t = 0.020$ s (1 MARK)

d The force on the racket will have the same magnitude but opposite direction to the force on the ball, $F_{on\ racket\ by\ ball} = -F_{on\ ball\ by\ racket}$

$F_{on\ racket\ by\ ball} = 230$ N to the left (2 MARKS)

14 [The initial momentum of the system is equal to the momentum of the 1.5 kg block: $\Sigma p_i = p_1 = m_1 u_1 = 1.5 u_1$ kg m s^{-1} or N s.[1]] [The final momentum of the system to the right is equal to the sum of the momentum of the 3.0 kg block and the 1.5 kg block: $\Sigma p_f = p_2 + p_1 = m_2 v_2 + m_1 v_1 = 3.0 v_2 - 1.5 v_1$ kg m s^{-1} or N s.[2]][Through the law of conservation of momentum, the initial momentum will be equal to the final momentum: $1.5 u_1 = 3.0 v_2 - 1.5 v_1$.[3]][Therefore, the final momentum of the 3.0 kg block will be the addition of the initial and final magnitude of momentum of the 1.5 kg block, $3.0 v_2 = 1.5 u_1 + 1.5 v_1$[4]] [consistent with the law of conservation of momentum.[5]]

- I have referenced the initial momentum of the system.[1]
- I have referenced the final momentum of the system.[2]

- I have used the relevant theory: the law of conservation of momentum.[3]
- I have explicitly addressed the greater momentum of the 3 kg block.[4]
- I have related my answer to the context of the question.[5]

Previous lessons

15 **a** $V_{pc} = IR_{pc}$ $\therefore 5.0 = I \times 4.0$

$I = 1.25 = 1.3$ A (1 MARK)

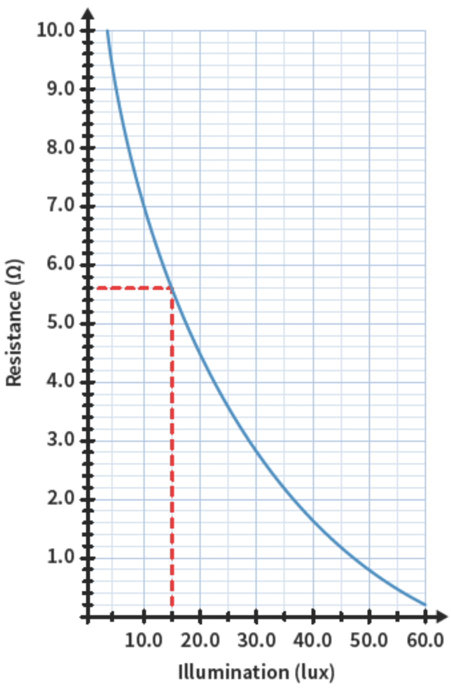
b $V_{source} = V_{LDR} + V_{pc}$ $\therefore 12 = V_{LDR} + 5.0$

$V_{LDR} = 7.0$ V (1 MARK)

$V_{LDR} = IR_{LDR}$ $\therefore 7.0 = 1.25 \times R_{LDR}$ (1 MARK)

$R_{LDR} = 5.6\ \Omega$ (1 MARK)

c For the resistance of the light dependent resistor to be 5.6 Ω, the luminosity will be 15 lux. (1 MARK)



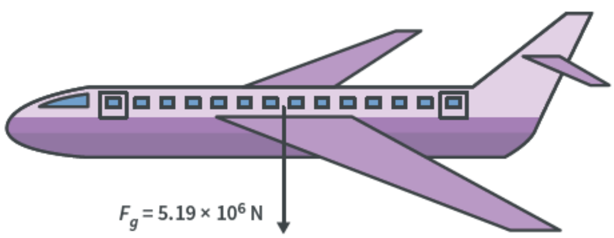
This content was covered in Lesson 5A.

16 **a** 530 tonnes = 530×10^3 kg = 5.30×10^5 kg

$F_g = mg = 5.30 \times 10^5 \times 9.80$ (1 MARK)

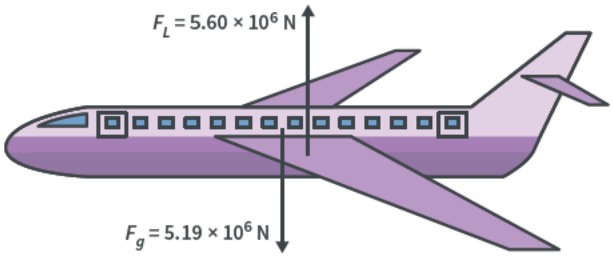
$F_g = 5.194 \times 10^6 = 5.19 \times 10^6$ N vertically downwards (1 MARK)

b



- I have drawn the force due to gravity acting vertically downwards.
- I have correctly labelled the force due to gravity vector.

c



- I have drawn the lift force acting vertically upwards.
- I have correctly labelled the lift force vector.
- I have drawn the lift force slightly larger than the force due to gravity.

d Take up as positive:

$F_{net} = F_L - F_g = 5.60 \times 10^6 - 5.194 \times 10^6$

$F_{net} = 4.06 \times 10^5$ N (1 MARK)

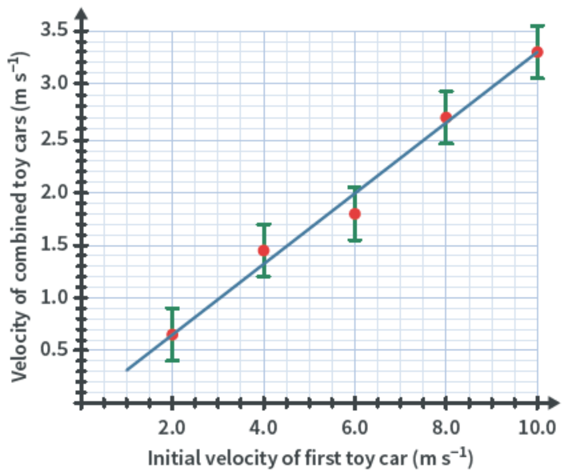
$F_{net} = ma$ $\therefore 4.06 \times 10^5 = 5.30 \times 10^5 \times a$ (1 MARK)

$a = 0.77$ m s^{-2} (1 MARK)

This content was covered in Lesson 9A.

Key science skills

17 **a**



- I have correctly labelled both axes including units.
- I have included an appropriate and consistent scale.
- I have correctly plotted each point of data.
- I have included correct uncertainty bars.
- I have drawn a line of best fit.

b $m_1 \times u = (m_1 + m_2) \times v$ $\therefore 1 \times u = (1 + m_2) \times v$

$gradient = \frac{rise}{run} = \frac{v}{u} = \frac{1}{1+m_2}$ (1 MARK)

Using any two points on the line of best fit:

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{3.3 - 0.8}{10.0 - 2.5} = 0.333$ (1 MARK)

$0.333 = \frac{1}{1+m_2}$ kg

$m_2 = 2$ kg (1 MARK)

10B Work and kinetic energy

Theory review questions

1 **a** $2E$ **b** $4E$ **c** $\frac{1}{16}E$

d $\frac{1}{2}E$ **e** E

2 **a** $W_{0-10} = P$

b $W_{0-35} = P + Q + R$

c $W_{10-50} = Q + R + S$

3 **a** I **b** III **c** II

d II **e** III **f** III

4 Power; large; does not always mean

Deconstructed exam-style question

5 **a** C **b** D **c** A

d The two forces acting on m_2 are the force due to gravity and the tension force.

$F_{net\,m_2} = 3.8g - T = m_2 a_2$

$3.8 \times 9.8 - T = 3.8 \times 3.77$, $T = 22.91$ N (1 MARK)

Considering m_1:

$F_{net\,m_1} = T - 15 = 22.91 - 15 = 7.91$ N (1 MARK)

$W = Fs = \Delta KE = KE_f - KE_i = 40$ J, since the block starts from rest. (1 MARK)

$7.91 \times s = 40 \;\therefore s = 5.1$ m (1 MARK)

Exam-style questions

This lesson

6 **a** $W = Fs = 40 \times 4.5 = 1.8 \times 10^2$ J (1 MARK)

b $\Delta KE = W = 1.8 \times 10^2$ J (1 MARK)

$KE_i = 0$ J, since the box starts from rest. $\therefore KE_f = 1.8 \times 10^2$ J (1 MARK)

7 [Work is defined as a force that causes a change in the energy of an object.[1]][Whilst the person is applying a force equal to the gravitational force acting on the object, the force is not causing the object to be displaced in the direction which it is being applied in.[2]][Therefore the energy of the object is not changing and so no work is being done.[3]]

- I have explicitly addressed what work is.[1]
- I have justified my answer by discussing that the applied force causes no displacement.[2]
- I have explicitly addressed why no work is being done in this context.[3]

8 $P = \frac{E}{t} = \frac{18 \times 10^3}{22} = 8.2 \times 10^2$ W (1 MARK)

9 $F_{net} = 0$, since books are being lifted at a constant speed

$F_{net} = 0 = F_{lift} - F_g$, $\therefore F_{lift} = F_g = mg = 2.5 \times 9.8 = 24.5$ N (1 MARK)

$W = Fs = 24.5 \times 1.5 = 37$ J (1 MARK)

10 **a** $\Delta KE = W = 32.5$ J

$KE_i = 0$, since the car starts from rest

$\therefore KE_f = 32.5$ J (1 MARK)

$KE_f = \frac{1}{2}mv^2 \;\therefore \frac{1}{2} \times 0.65 \times v^2 = 32.5$

$v = 10$ m s^{-1} (1 MARK)

b $KE_f = 32.5$ J (1 MARK)

$KE_f = \frac{1}{2}mv^2 \;\therefore \frac{1}{2} \times m \times 6.7^2 = 32.5$

$m = 1.4$ kg (1 MARK)

c $KE_f = 0.6 \times W = 0.6 \times 32.5 = 19.5$ J

Since mass is directly proportional to kinetic energy, $m = 0.6 \times 1.4 = 0.87$ kg (1 MARK)

11 **a** [Work is done when an applied force causes the displacement of an object parallel to the direction it is acting in.[1]][In this example, the horizontal component of the tension force displaces the sled to the right, however the vertical component does no work since the sled is not displaced up or down.[2]][Therefore the magnitude of the force doing work is 25cos(30°) N, and not 25 N.[3]]

- I have explicitly addressed when work is done in terms of force and displacement.[1]
- I have explicitly addressed why the horizontal component of the tension force is the only component that does work.[2]
- I have related my answer to the context of the question.[3]

b $W = \Delta KE = 150$ J, since the sled starts from rest.

$Fs = 150 \;\therefore 25\cos(30°) \times s = 150$ J (1 MARK)

$s = 6.9$ m (1 MARK)

12 **a** $W = \textit{area under graph} = \frac{1}{2} \times 8 \times 120 = 480$ J (1 MARK)

b $\Delta KE = \frac{1}{2}mv^2 - \frac{1}{2}mu^2 = \frac{1}{2} \times 80 \times 0.75^2 = 22.5$ J since the sofa starts from rest. (1 MARK)

Work done by friction opposes work done by Jock.

$\Delta KE = W_{Jock} - W_{friction} = 480 - F_{friction} \times 8$ (1 MARK)

$480 - 8 \times F_{friction} = 22.5$ J $\therefore F_{friction} = 57$ N (1 MARK)

c $\eta = \frac{\textit{useful energy out}}{\textit{total energy in}} = \frac{22.5}{480} = 0.047$ (1 MARK)

13 **a** magnitude of velocity does not change $\therefore \Delta KE = 0$ J (1 MARK)

b $W_{friction} = \Delta KE$

$\Delta KE = KE_f - KE_i = -80.0$ kJ, since the car ends at rest. (1 MARK)

$W_{friction} = F_{friction} \times s = -1700 \times s = -80.0 \times 10^3$ J

$s = 47.06 = 47.1$ m (1 MARK)

c $KE_1 = 80.0$ kJ when the car is travelling at v_1 m s^{-1}. KE_2 is the kinetic energy when the car is travelling at $v_2 = 1.1v_1$ m s^{-1}.

The mass is the same so the ratio between KE_2 and KE_1 is equal to the ratio between the squares of v_2 and v_1.

$\frac{KE_2}{KE_1} = \frac{(v_2)^2}{(v_1)^2} = \frac{(1.1v_1)^2}{v_1^{\,2}} = 1.1^2 \therefore KE_2 = 1.1^2 \times KE_1 = 96.8 \text{ kJ}$ (1 MARK)

$W_{friction} = F_{friction} \times s = -96.8 \times 10^3$ J

$1700 \times s = -96.8 \times 10^3$ J

$s = 56.94$ m (1 MARK)

The car would have travelled 56.94 − 47.06 = 9.88 m further. (1 MARK)

Previous lessons

14 $P = 8.5 \times 50 = 425 = 0.425$ kW

$t = 3 \times 24 = 72$ h (1 MARK)

$Cost = P \times t \times cost\ per\ kWh = 0.425 \times 72 \times 0.31 = \$9.49$ (1 MARK)

This content was covered in Lesson 5B.

15 Block is stationary, so $F_{net} = 0$ (1 MARK)

$F_{net} = F_{ds} - F_f = mg\sin(25°) - 18$

$m \times 9.8 \times \sin(25°) - 18 = 0$ (1 MARK)

$m = 4.3$ kg (1 MARK)

This content was covered in Lesson 9C.

Key science skills

16 [The results of Shian's experiment will be invalid.[1]][This is because her experimental design has more than one independent variable (work done and mass of the car),[2]][which means that the effect that the work done has on the dependent variable (final velocity) cannot be determined.[3]]

- I have related my answer to the context of the question.[1]
- I have justified my answer by stating what the two independent variables are.[2]
- I have justified my answer by stating how this will affect the dependent variable.[3]

10C Gravitational potential energy

Theory review questions

1 B. As gravitational potential energy is proportional to mass, for two objects at the same height the object with a greater mass will have more gravitational potential energy.

2 A. The final velocity of the ball depends only on the height it was dropped from, its initial velocity, and the strength of the gravitational field.

3 C. As the gravitational potential energy of the bowling ball is greater before it is dropped, it will have more kinetic energy when it reaches the ground.

4 B. As gravitational potential energy is proportional to height, for two objects of the same mass the object at a greater height will have more gravitational potential energy.

5 kinetic energy; conserved; gravitational potential energy; kinetic energy

6 C. We consider the initial kinetic and gravitational potential energy and recognise that the final gravitational potential energy is equal to zero.

7 B. The change in gravitational potential energy that is useful here is that between points *A* and *B*.

8 C. The change in gravitational potential energy that is useful here is that between points *A* and *C*.

Deconstructed exam-style questions

9 **a** A. Although you can use $KE_i + GPE_i = KE_f + GPE_f$ to find the final velocity, it is much easier to apply $v = \sqrt{-2g\Delta h + u^2}$.

b C. Energy is always conserved so the kinetic energy is converted into gravitational potential energy as the cart approaches the top of the loop-the-loop.

c B. The cart will lose kinetic energy so it must decrease in speed.

d At the top of the loop-the-loop:

$KE = \frac{1}{2}mv^2 \therefore 2.4 \times 10^5 = \frac{1}{2} \times 1.2 \times 10^3 \times v^2$ (1 MARK)

$v = 20 \text{ m s}^{-1}$ (1 MARK)

$v = \sqrt{-2g\Delta h + u^2} \therefore 20 = \sqrt{-2 \times 9.8 \times (40 - 0) + u^2}$ (1 MARK)

$u = 34.4 = 34 \text{ m s}^{-1}$ (1 MARK)

Exam-style questions

This lesson

10 $\Delta GPE = mg\Delta h \therefore 1.76 \times 10^5 = m \times 9.8 \times (1000 - 750)$ (1 MARK)

$m = 71.8 = 72$ kg (1 MARK)

11 **a** [Graph A.[1]][When the rock's height is a maximum and it is at rest, all its energy is stored as gravitational potential energy and so will be at its maximum.[2]][When its height is a minimum, its energy has been linearly converted into kinetic energy and it has no gravitational potential energy.[3]]

- I have explicitly addressed which graph shows gravitational potential energy as a function of height.[1]
- I have explicitly addressed the gravitational potential energy at the maximum height.[2]
- I have explicitly addressed the gravitational potential energy at the minimum height.[3]

b [Graph B.[1]][When the height is a maximum the ball has zero kinetic energy.[2]][As the ball's height decreases it loses gravitational potential energy linearly which is converted to kinetic energy since energy must be conserved.[3]]

- I have explicitly addressed which graph shows *KE* as a function of height.[1]
- I have explicitly addressed the kinetic energy at the maximum height.[2]
- I have used the relevant theory: conservation of energy.[3]

c Energy is conserved. So all initial *GPE* is converted to final *KE*. (1 MARK)

$KE_f = GPE_i = mg\Delta h = 1.0 \times 1.62 \times (0 - 15) = -24.3$

$KE_f = 24$ J (1 MARK)

d $v = \sqrt{-2g\Delta h + u^2} = \sqrt{-2 \times 1.62 \times (3.0 - 15) + 0^2}$ (1 MARK)

$v = 6.2 \text{ m s}^{-1}$ (1 MARK)

12 **a** The stone gained gravitational potential energy. (1 MARK)

b $\Delta GPE = area\ under\ graph = (40 - 10) \times 4.9$ (1 MARK)

$\Delta GPE = 147 \text{ J}$ (1 MARK)

c Measure the *GPE* from $h = 10$ m.

$KE_i + GPE_i = KE_f + GPE_f \therefore \frac{1}{2} \times 0.50 \times u^2 + 0 = 0 + 147$ (1 MARK)

$u = 24 \text{ m s}^{-1}$ (1 MARK)

13 **a** $v = \sqrt{-2g\Delta h + u^2} \therefore 46 = \sqrt{-2 \times 9.8 \times (0.0 - 100) + u^2}$ (1 MARK)

$u = 12.5 \text{ m s}^{-1}$ (1 MARK)

b $KE_i + GPE_i = KE_f + GPE_f \therefore KE_i + m_B g\Delta h = \frac{1}{2} \times m_B \times v_A{}^2 + 0$ (1 MARK)

$KE_i + 68 \times 9.8 \times (75 - 0) = \frac{1}{2} \times 68 \times 46^2$ (1 MARK)

$KE = 21\,964 = 2.2 \times 10^4 \text{ J}$ (1 MARK)

14 **a** Total energy is conserved so $E_{total\ Q} = E_{total\ P}$

$E_{total\ P} = KE + GPE = \frac{1}{2}mv^2 + mg\Delta h = \frac{1}{2} \times 950 \times 12.0^2 + 950 \times 9.8 \times 70$
(1 MARK)

$E_{total\ Q} = 720\,100 = 7.2 \times 10^5 \text{ J}$ (1 MARK)

b $E_{total} = E_{total\ R} = KE + GPE = KE + mg\Delta h$

$7.2 \times 10^5 = KE + 950 \times 9.8 \times (30 - 0)$ (1 MARK)

$KE = 440\,800 = 4.4 \times 10^5 \text{ J}$ (1 MARK)

15 **a** Energy is conserved: $E_f = GPE_i = mg\Delta h = 25 \times 9.8 \times 2.5$ (1 MARK)

$E_f = 612 = 6.1 \times 10^2 \text{ J}$ (1 MARK)

b $t = \frac{E_f}{P} = \frac{612.5}{2.0} = 306 = 3.1 \times 10^2 \text{ s}$ (2 MARKS)

Previous lessons

16 [Fuses protect devices by preventing the flow of dangerous amounts of current.[1]][The fuse has a wire inside that melts (or 'blows') when the current exceeds the rated amount.[2]][Other safety devices are more commonly used now as fuses require replacement every time they blow and they do not protect from electric shock.[3]]

- I have explicitly addressed how fuses protect devices.[1]
- I have used the relevant theory: how fuses work.[2]
- I have explicitly addressed why fuses are less commonly used than other safety devices.[3]

This content was covered in Lesson 5C.

17 Defining anticlockwise as positive:

$\tau_A = r_A F_A = 0.20 \times 3.0 \times 9.8 = 5.88 \text{ N m}^{-1}$ (1 MARK)

$\tau_B = r_B F_B = 0.35 \times 2.0 \times 9.8 = 6.86 \text{ N m}^{-1}$ (1 MARK)

$\Sigma\tau = \tau_A - \tau_B = 5.88 - 6.86 = -0.98 = 9.8 \times 10^{-1} \text{ N m}^{-1}$ clockwise (1 MARK)

This content was covered in Lesson 9D.

Key science skills

18 [The experiment is invalid as a control variable has changed.[1]][The size of the ball needs to be maintained throughout.[2]][If Bella uses a ball with the same radius or excludes the 4.0 kg ball from the data the experiment will be valid.[3]]

- I have explicitly addressed the validity of the experiment.[1]
- I have used the relevant theory: control variables.[2]
- I have explicitly addressed the 4.0 kg ball.[3]

10D Springs

Theory review questions

1 linearly with; with the square of

2 gradient; area under the graph

3 B. At position *A* the ball is moving and is above position *B* but the spring is at its natural length, so the system initially has only kinetic energy and gravitational potential energy. At position *B* the ball has compressed the spring but is not moving and is at its lowest point, so the system only has strain potential energy.

4 A. The balls are the same mass and hence have the same weight force acting downwards, Spring 1 requires less displacement to oppose this force so it has the greater spring constant by Hooke's Law.

5 C. The two balls are at rest on the springs meaning they are in the equilibrium position and the spring force is equal to the weight force of the balls, $mg = k\Delta x$. As the balls have the same mass, the spring force for each spring is the same.

6 B. The *SPE* in the two springs will be equal to the change in *GPE* of the balls as the spring is compressed from its natural length to its equilibrium position. This difference is greater in Spring 2 as it is displaced further, and hence it has more *SPE*.

7 C. The spring force-displacement graph for an ideal spring will be represented by a straight line. The line will pass through the origin of the graph as the restoring force produced by a spring with zero displacement is zero.

Deconstructed exam-style questions

8 **a** C. $F_s = k\Delta x \therefore 60 = k \times 0.35$

$k = 171 \text{ N m}^{-1}$

b B. As the bean bag is not moving, its kinetic energy is zero. It is compressing the spring and has non-zero displacement above its final position so it has strain and gravitational potential energy.

c B. The spring is no longer being compressed so there is zero strain potential energy. As the bean bag is moving and is above the ground, it has both kinetic and gravitational potential energy.

d C. The law of conservation of energy states that the total initial energy will be equal to the total final energy, hence $SPE_i + GPE_i = KE_f + GPE_f$.

e $F_s = k\Delta x \therefore 60 = k \times 0.35$ (1 MARK)

$k = 171 \text{ N m}^{-1}$ (1 MARK)

Consider the initial position to be the compressed spring and final position to be just before striking Hook Slaw.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$SPE_i + GPE_i = KE_f + GPE_f \therefore \frac{1}{2}k(\Delta x)^2 + mgh_i = \frac{1}{2}mv^2 + mgh_f$ (1 MARK)

$\frac{1}{2} \times 171 \times (\Delta x)^2 + 0.15 \times 9.8 \times 2.60 =$

$\frac{1}{2} \times 0.15 \times 6.0^2 + 0.15 \times 9.8 \times 1.50$ (1 MARK)

$\Delta x = 0.11$ m (1 MARK)

Exam-style questions

This lesson

9 a C (1 MARK)

The spring constant is the gradient of a spring force-displacement graph.

$gradient = \frac{rise}{run} = \frac{\Delta F}{\Delta x} = \frac{100 - 0}{0.50 - 0} = 200 \text{ N m}^{-1}$

b A (1 MARK)

The initial kinetic energy of the model car is equal to the strain potential energy of the compressed spring.

Strain potential energy is equal to the area under a spring force-displacement graph.

$area\ under\ graph = SPE = \frac{1}{2} \times 0.80 \times 160 = 64 \text{ J}$

c B (1 MARK)

This is the vertical axis value of the graph at 0.40 m displacement.

$F_s = k\Delta x = 200 \times 0.40 = 80 \text{ N}$

10 a $F_s = k\Delta x = 200 \times 0.60$

$F_s = 1.2 \times 10^2 \text{ N}$ (1 MARK)

b $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 200 \times 0.60^2$ (1 MARK)

$SPE = 36 \text{ J}$ (1 MARK)

c $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$SPE_i = KE_f \therefore 36 = \frac{1}{2}mv^2$ (1 MARK)

$36 = \frac{1}{2} \times 0.35 \times v^2$ (1 MARK)

$v = 14 \text{ m s}^{-1}$ (1 MARK)

11 a Any number of masses from 1 to 3 can be considered – we will use 2.

$F_g = F_s \therefore mg = k\Delta x$

$2 \times 30 \times 10^{-3} \times 9.8 = k \times 20 \times 10^{-2}$ (1 MARK)

$k = 2.94 = 2.9 \text{ N m}^{-1}$ (1 MARK)

b $\Delta x = total\ length - unstretched\ length = 80 - 50 = 30$ cm

$SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 2.94 \times (30 \times 10^{-2})^2$ (1 MARK)

$SPE = 0.13 \text{ J}$ (1 MARK)

12 a To find k, use a conservation of energy approach considering the initial position of the ball and when the spring is compressed.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$KE_i + GPE_i = SPE \therefore \frac{1}{2}mu^2 + mgh = \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$\frac{1}{2} \times 0.40 \times 2.0^2 + 0.40 \times 9.8 \times 1.5 = \frac{1}{2} \times k \times (30 \times 10^{-2})^2$ (1 MARK)

$k = 148 = 1.5 \times 10^2 \text{ N m}^{-1}$ (1 MARK)

b The maximum speed of the ball will be just before it touches the spring, when all its energy is kinetic energy.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$KE_i + GPE_i = KE_f \therefore \frac{1}{2}mu^2 + mgh = \frac{1}{2}mv^2$ (1 MARK)

$\frac{1}{2} \times 0.40 \times 2.0^2 + 0.40 \times 9.8 \times 1.5 = \frac{1}{2} \times 0.40 \times v^2$ (1 MARK)

$v = 5.78 = 5.8 \text{ m s}^{-1}$ (1 MARK)

c At the maximum height, gravitational potential energy will be the only form of energy.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$KE_i + GPE_i = GPE_f \therefore \frac{1}{2}mu^2 + mgh = mgs$ (1 MARK)

$\frac{1}{2} \times 0.40 \times 2.0^2 + 0.40 \times 9.8 \times 1.5 = 0.40 \times 9.8 \times s$ (1 MARK)

$s = 1.7$ m (1 MARK)

13 a To find the spring constant, k, consider the initial position from the diagram and the final position where the spring is compressed by 0.20 m.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$KE_i = GPE_f + SPE_f \therefore \frac{1}{2}mu^2 = mg(h + \Delta x) + \frac{1}{2}k(\Delta x)^2$

$\frac{1}{2} \times 10 \times 5.0^2 = 10 \times 9.8 \times (1.0 + 0.20) + \frac{1}{2} \times k \times 0.20^2$ (1 MARK)

$k = 3.7 \times 10^2 \text{ N m}^{-1}$ (1 MARK)

b Take down as positive.

$F_{net} = ma \therefore F_g + F_s = ma$

$mg + k\Delta x = ma \therefore 10 \times 9.8 + 3.7 \times 10^2 \times 0.20 = 10 \times a$ (1 MARK)

$a = 17 \text{ m s}^{-2}$ downwards (1 MARK)

c Consider the initial position and the final position when the spring is compressed by 0.05 m.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$KE_i = KE_f + GPE_f + SPE_f \therefore \frac{1}{2}mu^2 = \frac{1}{2}mv^2 + mg(h + \Delta x) + \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$\frac{1}{2} \times 10 \times 5.0^2 =$

$\frac{1}{2} \times 10 \times v^2 + 10 \times 9.8 \times (1.0 + 0.05) + \frac{1}{2} \times 3.7 \times 10^2 \times 0.05^2$ (1 MARK)

$v = 2.1 \text{ m s}^{-1}$ (1 MARK)

d 5.0 m s^{-1} to the left (1 MARK)

By the law of conservation of energy the total final and total initial energy will be equal. As kinetic energy is the only energy at this position and no energy has been lost, the speed will be the same.

Previous lessons

14 [A circuit breaker protects from fire and damage to appliances whereas a residual current device protects users from electric shock.[1]][A circuit breaker stops the supply of current to a household circuit when a current overload is detected[2]][whilst a residual current device measures the difference in current between the active and neutral wires and stops the current in the circuit when this difference is not zero.[3]]

- I have explicitly addressed the function of circuit breakers and residual current devices.[1]
- I have explicitly addressed the operation of circuit breakers.[2]
- I have explicitly addressed the operation of residual current devices.[3]

This content was covered in Lesson 5C.

15 a Consider rotational equilibrium: $\Sigma\tau_{anticlockwise} = \Sigma\tau_{clockwise}$

Consider the torques measured around point *Y*:

$\tau_{bridge} + \tau_{car} = \tau_{left\ building}$

$r_B \times F_{g\ bridge} + r_C \times F_{g\ car} = r_{left\ building} \times F_X$

$10 \times 5.0 \times 10^4 \times 9.8 + 6.5 \times 2.2 \times 10^3 \times 9.8 = 20 \times F_X$ (1 MARK)

$F_X = 2.52 \times 10^5 = 2.5 \times 10^5$ N (1 MARK)

b Consider translational equilibrium: $\Sigma F = 0 \;\therefore F_X + F_Y = F_{g\ car} + F_{g\ bridge}$

$2.52 \times 10^5 + F_Y = 2.2 \times 10^3 \times 9.8 + 5.0 \times 10^4 \times 9.8$ (1 MARK)

$F_Y = 2.6 \times 10^5$ N (1 MARK)

OR

Consider rotational equilibrium: $\Sigma\tau_{clockwise} = \Sigma\tau_{anticlockwise}$

Consider the torques measured around point *X*:

$\tau_{bridge} + \tau_{car} = \tau_{right\ building}$

$r_B \times F_{g\ bridge} + r_C \times F_{g\ car} = r_{right\ building} \times F_Y$

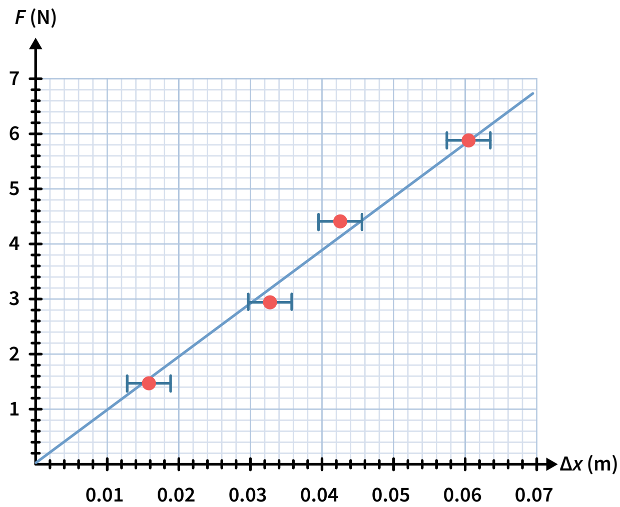
$10 \times 5.0 \times 10^4 \times 9.8 + (20 - 6.5) \times 2.2 \times 10^3 \times 9.8 = 20 \times F_Y$ (1 MARK)

$F_Y = 2.6 \times 10^5$ N (1 MARK)

This content was covered in Lesson 9E.

Key science skills

16 a



- I have drawn compression on the horizontal axis.
- I have drawn force on the vertical axis.
- I have labelled both axes and included units.
- I have used an appropriate and consistent scale.
- I have plotted each point of data.
- I have included the correct uncertainty bars.
- I have included a straight line of best fit which passes through all uncertainty bars.

b The spring constant is the gradient of a spring force-compression graph.

Use two points on the line of best fit to determine rise and run.

$gradient = k = \frac{rise}{run} = \frac{3.8 - 0}{0.04 - 0}$ (1 MARK)

$k = 95$ N m^{-1} (1 MARK)

Depending on the line of best fit drawn, answers between 90 N m^{-1} and 100 N m^{-1} are acceptable.

Chapter 10 Review

Section A

1 A

$m\Delta v = F\Delta t$

$56 \times 10^{-3} \times 50 = 140 \times \Delta t \;\therefore \Delta t = 0.020$ s

2 B

$KE_i + GPE_i = KE_f + GPE_f$

$KE_i = GPE_f \;\therefore \frac{1}{2}mu^2 = mgh_f$

$\frac{1}{2} \times 300 \times 10^{-3} \times 5.0^2 = 300 \times 10^{-3} \times 9.8 \times \Delta h \;\therefore h_f = h = 1.3$ m

3 D. By the law of conservation of energy, the total initial and final energies must be equal. At point *B*, the ball only has kinetic energy and since no energy was lost due to friction, the speed will be the same as at point *A*.

4 B. Since $SPE = \frac{1}{2}k(\Delta x)^2$, it is proportional to the square of the extension. So if the extension increases by a factor of 4, the *SPE* increases by a factor of $4^2 = 16$. Therefore $SPE = 16 \times 50 = 800$ J.

5 C. Before the collision, $\Sigma p_i = m_1 u$; after the collision, $\Sigma p_f = (m_1 + m_2)v$. Since $\Sigma p_i = \Sigma p_f$ and $m_1 + m_2 > m_1$, this means that $v < u$.

Section B

6 a $F_{net} = F_{applied} - F_s = 0$

$F_s = k\Delta x \;\therefore 70 = k \times 0.35$

$k = 2.0 \times 10^2$ N m^{-1} (1 MARK)

b $KE_i + SPE_i = KE_f + SPE_f$

$KE_f = SPE_i = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times (2.0 \times 10^2) \times 0.35^2 = 12.25$ J (1 MARK)

Work done by friction = Δ*KE*

$\therefore F_f \times s = 12.25$ (1 MARK)

$s = \frac{12.25}{3.10} = 3.95 = 4.0$ m (1 MARK)

c $I = m\Delta v = 2.5 \times 1.8 = 4.5$ kg m s^{-1} (1 MARK)

7 a [The change in momentum is given by $\Delta p = m(v - u) = (450 \times 10^{-3}) \times (9.0 - (-12.0)) = 9.5$ kg m s^{-1} upwards.[1]] [This does not violate the law of conservation of momentum.[2]] [Whilst the final momentum of the ball is smaller in magnitude than the initial momentum, Newton's Third Law tells us that the ground experiences an impulse downwards to conserve the total momentum.[3]]

- I have used the relevant theory: calculating the change in momentum.[1]
- I have explicitly addressed whether momentum is conserved.[2]
- I have justified my answer by addressing the change in momentum of the ground.[3]

b $v = \sqrt{-2g\Delta h + u^2}$ $\therefore 0.0 = \sqrt{-2 \times 9.8 \times \Delta h + 9.0^2}$ (1 MARK)

$h = 4.1$ m (1 MARK)

c $KE_i + SPE_i + GPE_i = KE_f + SPE_f + GPE_f$

$SPE_i = KE_f + GPE_f$ $\therefore \frac{1}{2}k(\Delta x)^2 = \frac{1}{2}mv^2 + mgh_f$ (1 MARK)

$\frac{1}{2} \times k \times (5.8 \times 10^{-2})^2 =$

$\frac{1}{2} \times (450 \times 10^{-3}) \times 9.0^2 + (450 \times 10^{-3}) \times 9.8 \times (5.8 \times 10^{-2})$ (1 MARK)

$k = 1.1 \times 10^4$ N m^{-1} (1 MARK)

8 a Define positive velocity as to the right.

$\Sigma p_i = m_X u_X + m_Y u_Y = (4.5 \times 10^3) \times (7.0) + (2.6 \times 10^3) \times (-3.7)$

$\Sigma p_i = 2.19 \times 10^4$ kg m s^{-1} to the right (1 MARK)

By the law of conservation of momentum, $\Sigma p_i = \Sigma p_f$.

$\Sigma p_f = 2.19 \times 10^4$ kg m s^{-1} to the right

$\Sigma p_f = m_{total} v = (m_X + m_Y) \times v$

$2.19 \times 10^4 = (4.5 \times 10^3 + 2.6 \times 10^3) \times v$ (1 MARK)

$v = 3.08 = 3.1$ m s^{-1} to the right (1 MARK)

b $I_Y = \Delta p_Y = m_Y(v_Y - u_Y) = 2.6 \times 10^3 \times (3.08 - (-3.7)) = 1.76 \times 10^4$ kg m s^{-1} to the right (1 MARK)

$I_Y = F_{avg}\Delta t$ $\therefore 1.76 \times 10^4 = 25\,000 \times \Delta t$

$\Delta t = 0.71$ s (1 MARK)

c [It is impossible for *Z* to remain stationary since this would be a violation of the law of conservation of momentum.[1]] [The initial momentum of carts *X* and *Y* is 2.2×10^4 kg m s^{-1} to the right from part **a**, and since *Z* is stationary its initial momentum is 0 kg m s^{-1}. Therefore, the final momentum of the system *X*-*Y*-*Z* must also be to the right.[2]] [This cannot be the case if the combined carts have zero velocity immediately after the collision.[3]]

- I have used the relevant theory: the law of conservation of momentum.[1]
- I have justified my answer by referring to the initial and final momentums of the system.[2]
- I have explicitly addressed the reason why *Z* remaining stationary is impossible.[3]

9 a At the equilibrium position, $F_{net} = F_s - F_g = 0$

$k\Delta x = mg$ $\therefore 300 \times \Delta x = 75.0 \times 9.8$

$\Delta x = 2.5$ m (1 MARK)

b Define initial position as the point he jumps from and final position as the lowest point of the fall.

$KE_i + SPE_i + GPE_i = KE_f + SPE_f + GPE_f$

$GPE_i = SPE_f$ $\therefore mgh_f = \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$75.0 \times 9.8 \times 65.0 = \frac{1}{2} \times 300 \times (\Delta x)^2$, $\Delta x = 17.8$ m (1 MARK)

Therefore the natural length of the bungee cord is $65.0 - 17.8 = 47.2 = 47$ m. (1 MARK)

c $v = \sqrt{-2g\Delta h + u^2}$ $\therefore v = \sqrt{-2 \times 9.8 \times (0 - 25) + 0^2}$ (1 MARK)

$v = 22$ m s^{-1} (1 MARK)

Unit 2, AOS 1 Review

Section A

1 B

distance = *area under speed-time graph*

distance $= 24 \times 0.25 + \frac{1}{2} \times 1.5 \times 24 = 24$ m

This content was covered in Lesson 8B.

2 D

$I = F\Delta t = m\Delta v$

$F \times 1.5 = 280 \times 24$ $\therefore F = 4480 = 4.5 \times 10^3$ N = 4.5 kN

This content was covered in Lesson 10A.

3 C. The net force perpendicular to the plane is given by $F_{net} = F_N - F_g\cos(\theta) = 0$, since the ball's acceleration perpendicular to the plane is 0. This means that $F_g = \frac{F_N}{\cos(\theta)}$, so $F_N < F_g$.

This content was covered in Lesson 9C.

4 B. The net force acting on the entire system is given by $F_{net} = m_A g - m_B g$. The two blocks have zero acceleration, which means $F_{net} = 0$. Therefore $m_A g = m_B g$ and $m_A = m_B$.

This content was covered in Lesson 9C.

5 B. Taking torques about the pivot point, both F_2 and F_3 produce anticlockwise torques whilst F_1 produces no torque since it passes through the fulcrum. There is no force to provide a clockwise torque so the system cannot be in rotational, and therefore static, equilibrium.

This content was covered in Lessons 9D and 9E.

Section B

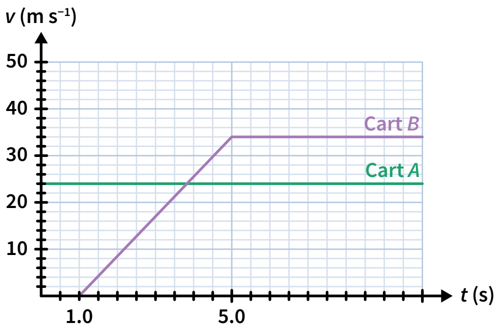
6 a Given: $v = 39.0$ m s^{-1}, $s = 150$ m, $t = 5.50$ s; Required: u

$s = \frac{1}{2}(u + v)t \;\therefore\; 150 = \frac{1}{2}(u + 39.0) \times 5.50$ (1 MARK)

$u = 15.546 = 15.5$ m s^{-1} (1 MARK)

This content was covered in Lesson 8C.

b



First find the final velocity of cart B:

Given: $u = 0$ m s^{-1}, $a = 8.5$ m s^{-2}, $t = 4.0$ s; Required: v

$v = u + at = 0 + 8.5 \times 4 = 34$ m s^{-1} (1 MARK)

Displacement equals area under velocity-time graph.

$s_A = 24t$, $s_B = \frac{1}{2} \times 4.0 \times 34 + 34 \times (t - 5.0) = 34t - 102$ (1 MARK)

At the end of the track, $s_A = s_B \;\therefore\; 24t = 34t - 102$

$t = 10.2$ s (1 MARK)

$s_A = 24 \times 10.2 = 244.8$ m

The track would have to be 2.4×10^2 m long. (1 MARK)

OR

We will take t to be the amount of time passed since cart A started moving.

When $t = 5$ s:

$s_A = ut + \frac{1}{2}at^2 \;\therefore\; s_A = 24 \times 5 + \frac{1}{2} \times 0 \times 5^2 = 120$ m;

$s_B = 0 \times (5 - 1) + \frac{1}{2} \times 8.5 \times (5 - 1)^2 = 68$ m (1 MARK)

$s_B < s_A$ so cart B catches up to cart A when $t > 5$ s:

$v_B = u + at \;\therefore\; v_B = 0 + 8.5 \times (5 - 1) = 34$ m s^{-2}

$s_A = 24 \times t$; $s_B = s_{B,t=5} + v_B(t - 5) = 68 + 34(t - 5)$ (1 MARK)

When cart B catches up to cart A:

$s_A = s_B \;\therefore\; 24 \times t = 68 + 34(t - 5) \;\therefore\; t = 10.2$ s (1 MARK)

at $t = 10.2$ s: $s_A = 24 \times t = 24 \times 10.2 = 244.8$ m

The track would have to be 2.4×10^2 m long. (1 MARK)

This content was covered in Lessons 8B and 8C.

c $GPE_i + KE_i = GPE_f + KE_f$

$mgh_i + \frac{1}{2}mu^2 = mgh_f + \frac{1}{2}mv^2$

$9.8 \times 25.0 + \frac{1}{2} \times 15^2 = 9.8 \times 15.0 + \frac{1}{2}v^2$ (1 MARK)

$v = 20.5 = 21$ m s^{-1} (1 MARK)

This content was covered in Lesson 10C.

7 a In the horizontal direction: $F_x = 30.0 + 15.0\cos(45.0°) - 22.5 = 18.11$ N

In the vertical direction:
$F_y = 25.0 - 15.0\sin(45.0°) = 14.39$ N upwards (1 MARK)

Magnitude of $F_{net} = \sqrt{(18.11)^2 + (14.39)^2} = 23.13$ N (1 MARK)

$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{14.39}{18.11}\right) = 38.0°$ or $142°$ (1 MARK)

This content was covered in Lesson 9B.

b $\tau_{net} = \tau_{anticlockwise} - \tau_{clockwise} = 0$

$0.90 \times 30 + 1.7 \times F - 0.75 \times 45 = 0$ (1 MARK)

$F = 4.0$ N (1 MARK)

This content was covered in Lesson 9E.

8 a Perpendicular to the plane, $F_{net} = 0$

$F_{net} = F_N - mg\cos(35°) = 0 \;\therefore\; F_N - 2.50 \times 9.8\cos(35°) = 0$ (1 MARK)

$F_N = 20$ N (1 MARK)

This content was covered in Lesson 9C.

b Parallel to the plane, $F_{net} = ma = F_g\sin(35°) - F_f$

$2.50 \times 0.25 = 2.50 \times 9.8 \times \sin(35°) - F_f$ (1 MARK)

$F_f = 13.43 = 13$ N (1 MARK)

This content was covered in Lesson 9C.

c $W = Fs \;\therefore\; 16 = F_f \times s = 13.43 \times s$

$s = 1.191$ m (1 MARK)

$h = s \times \sin(35°) = 1.191 \times \sin(35°)$ m (1 MARK)

$h = 0.6831 = 0.68$ m

This content was covered in Lesson 10B.

d Given: $a = 0.25$ m s^{-2}, $s = 1.19$ m, $u = 0$ m s^{-1}; Required: v

$v^2 = u^2 + 2as \;\therefore\; v^2 = 2 \times 0.25 \times 1.191$ (1 MARK)

$v = 0.7717 = 0.77$ m s^{-1}

OR

$GPE_i + KE_i = GPE_f + KE_f - W_{fric}$

$GPE_i = KE_f - W_{fric} \;\therefore\; mgh = \frac{1}{2}mv^2 - W_{fric}$

$0.250 \times 9.8 \times 0.6731 = \frac{1}{2} \times 2.50 \times v^2 - 16$ (1 MARK)

$v = 0.77$ m s^{-1}

This content was covered in Lessons 8C and 10C.

REVIEW

e $p_i = p_A + p_B = 2.50 \times 0.77 + 1.80v = 1.925 + 1.80v$ (1 MARK)

$p_f = (m_A + m_B) \times 0.50 = 2.15\ \text{kg m s}^{-1}$ (1 MARK)

By conservation of momentum, $p_i = p_f$.

$1.925 + 1.80v = 2.15\ \therefore v = 0.125 = 0.13\ \text{m s}^{-1}$ (1 MARK)

This content was covered in Lesson 10A.

9 **a** $k = gradient = \frac{800 - 0}{1.50 - 0} = 5.33 \times 10^2\ \text{N m}^{-1}$ (1 MARK)

This content was covered in Lesson 10D.

b Define the initial position to be at *Y* and the final position to be at *X*.

$GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = GPE_f + KE_f + SPE_f\ \therefore \frac{1}{2}k(\Delta x_Y)^2 = mgh_f + \frac{1}{2}mv^2 + \frac{1}{2}k(\Delta x_X)^2$ (1 MARK)

$\frac{1}{2} \times 5.33 \times 10^2 \times 0.75^2$
$= 0.800 \times 9.8 \times 0.40 + \frac{1}{2} \times 0.800 \times v^2 + \frac{1}{2} \times 5.33 \times 10^2 \times 0.35^2$ (1 MARK)

$v = 16.89 = 17\ \text{m s}^{-1}$ (1 MARK)

This content was covered in Lesson 10D.

c $GPE_i + KE_i = GPE_f + KE_f - W_{by\ air}$

$\frac{1}{2}mu^2 = mgh_f - W_{by\ air}\ \therefore \frac{1}{2} \times 0.800 \times 17.0^2 = 0.800 \times 9.8 \times 12.5 - W_{by\ air}$

$W_{by\ air} = 17.6\ \text{J}$ (1 MARK)

$\frac{W_{by\ air}}{KE_i} = \frac{17.6}{\frac{1}{2} \times 0.800 \times 17.0^2} \times 100 = 15.2 = 15\%$ of its energy is lost to air resistance. (1 MARK)

OR

Given: $u = 17\ \text{m s}^{-2}$, $a = -9.8\ \text{m s}^{-2}$, $v = 0\ \text{m s}^{-1}$; Required: s

$v^2 = u^2 + 2as\ \therefore 0^2 = 17^2 - 2 \times 9.8 \times s$ (1 MARK)

$s = 14.74\ \text{m}$

The rocket maintains $\frac{12.5}{14.74} = 0.85 = 85\%$ of its initial energy.
Therefore it loses 15% of its energy to air resistance. (1 MARK)

This content was covered in Lessons 8C and 10B.

10 M_1 system:

$a_{M_1} = a_{M_2} = 3.14\ \text{m s}^{-2}$ (1 MARK)

$F_{net\ M_1} = T - 150 = ma$ (1 MARK)

$T - 150 = 25 \times 3.14\ \therefore T = 228.5 = 2.3 \times 10^2\ \text{N}$ (1 MARK)

OR

M_2 system:

Taking downwards as positive, $F_{net} = ma\ \therefore F_g - T = ma$ (1 MARK)

$34 \times 9.8 - T = 34 \times 3.14$ (1 MARK)

$T = 226.4 = 2.3 \times 10^2\ \text{N}$ (1 MARK)

This content was covered in Lesson 9C.

11 **a** Given: $u = 0\ \text{m s}^{-1}$, $a = -9.8\ \text{m s}^{-2}$, $v = -18.0\ \text{m s}^{-1}$; Required: s

$v^2 = u^2 + 2as\ \therefore (-18.0)^2 = 0^2 - 2 \times 9.8 \times s$ (1 MARK)

$s = -16.53 = -17\ \text{m}$

Therefore the height is 17 m. (1 MARK)

OR

$GPE_i + KE_i = GPE_f + KE_f$

$\frac{1}{2}mu^2 = mgh_f\ \therefore \frac{1}{2}u^2 = gh_f\ \therefore \frac{1}{2} \times 18.0^2 = 9.8 \times h_f$ (1 MARK)

$h_f = 16.53 = 17\ \text{m}$ (1 MARK)

This content was covered in Lessons 8C and 10C.

b [The change in displacement of the ball is zero,[1]][and so by the symmetry of vertical motion (and energy conservation), the magnitude of the ball's final velocity will be equal to the magnitude of the ball's initial velocity.[2]][Therefore the final velocity of the ball will be 15.0 m s^{-1}, less than the 18.0 m s^{-1} she wanted.[3]]

I have referenced the change in displacement of the ball.[1]

I have used the relevant theory: symmetry of vertical motion or energy conservation.[2]

I have related my answer to the context of the question.[3]

This content was covered in Lessons 8B and 10C.

c Given: $a = -9.8\ \text{m s}^{-2}$, $v = -18.0\ \text{m s}^{-1}$, $s = -14.5\ \text{m}$; Required: t

Find the initial velocity using $v^2 = u^2 + 2as$

$(-18.0)^2 = u^2 + 2 \times (-9.8) \times (-14.5)\ \therefore u = -6.31\ \text{m s}^{-1}$, since the ball is thrown downwards. (1 MARK)

$v = u + at\ \therefore -18.0 = -6.31 - 9.8 \times t$ (1 MARK)

$t = 1.19 = 1.2\ \text{s}$ (1 MARK)

This content was covered in Lesson 8C.

12 **a** $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$mgh_i = \frac{1}{2}k(\Delta x)^2$, $h_i = \Delta x = L$ (1 MARK)

$mgL = \frac{1}{2}kL^2$, cancel an L on the LHS and RHS.

$3.2 \times 9.8 = \frac{1}{2} \times 75 \times L\ \therefore L = 0.836 = 0.84\ \text{m}$

This content was covered in Lesson 10C.

b $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$mgh_i = mgh_f + \frac{1}{2}mv^2 + \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$3.2 \times 9.8 \times 0.84 = 3.2 \times 9.8 \times 0.42 + \frac{1}{2} \times 3.2 \times v^2 + \frac{1}{2} \times 75 \times (0.42)^2$

$v = 2.02 = 2.0\ \text{m s}^{-1}$ (1 MARK)

This content was covered in Lesson 10D.

c At the equilibrium position, $F_{net} = F_s - F_g = 0$

$k\Delta x = mg \;\therefore 75 \times \Delta x = 3.2 \times 9.8$ (1 MARK)

$\Delta x = 0.42$ m

This content was covered in Lesson 10D.

d [From part **c** we know the midpoint (0.42 m) is the equilibrium position.[1]] [Above the midpoint the net force acts downwards so the falling mass is accelerating and gaining speed. Below the midpoint the net force acts upwards slowing down the mass. At the midpoint the forces due to gravity and the spring are equal and opposite (they are in equilibrium) so the acceleration of the mass is 0.[2]] [Therefore its maximum speed must occur at the equilibrium position.[3]]

- I have explicitly addressed that the midpoint is the equilibrium position.[1]
- I have used the relevant theory: forces acting on a mass-spring system.[2]
- I have explicitly addressed why the maximum speed will occur at the equilibrium position.[3]

This content was covered in Lessons 9A and 10D.

Concept discussion questions

2A

- The milk diffuses because of collisions between the milk particles and the water molecules, as they are all in random motion, which randomly spreads the milk particles throughout the tea.
- When the tea is very hot, the water molecules move quickly and collide more often with the milk particles, causing them to spread faster than when the tea is cold.

2B

Example responses:

- The heat travels via electromagnetic radiation from the Sun to the Earth, where it is absorbed by a particle in a leaf. The hotter leaf transfers this energy to air particles through conduction, which then rise due to the air's increased temperature (and lower density), transferring the energy via convection.
- Energy is carried by the electromagnetic radiation from the Sun, and is absorbed by air particles in Earth's atmosphere. These air particles rise due to the air now having a lower density from being at a higher temperature. The air then passes on the energy through conduction when its particles collide with another substance's particles.

2C

- A burn occurs when a large quantity of heat is transferred in a short period of time.
- Steam has a lot more internal energy stored as potential energy than water at 100°C.
- This means that the steam will transfer this large quantity of energy (the latent heat) to the skin that it touches as it condenses, causing severe burns. It does not decrease in temperature while it condenses so it will continue to transfer heat rapidly during this process.
- Water will cool down while it transfers heat, and so the rate of heat transfer will decrease.

2D

- When you push down the bicycle pump, you compress the air in it. This means you do work on the system.
- This increases the internal energy of the system: $\Delta U = Q + W$ where the work done on the system is considered a positive quantity. The increase in internal energy causes a corresponding increase in temperature (the average translational kinetic energy of the air molecules increases).
- The pump 'feels warm' because heat is transferring from the air to the pump and then to your hands. This in turn slightly decreases the internal energy of the air in the pump.

3A

- Information-carrying signals need to pass (be transmitted) through solid objects and travel long distances. They must also not interfere with other signals.
- Visible light cannot travel through obstacles such as buildings. It would be impractical to have visible light beams shining all around for the sake of communication technology in addition to the light that we use for sight. The visible region of the spectrum is very small, which means there is a limited range of frequencies (bandwidth) to be able to carry different signals.
- Gamma waves have incredibly high energy. This makes them difficult to produce and dangerous to people. They are also unable to travel very far through objects. This makes them unsuitable for communications technology.

3B

- Shiny/reflective objects are not as good at emitting (or absorbing) radiation.
- A kettle is designed to heat water quickly and efficiently.
- A kettle heats up water with a metal coil that it heats with electrical energy (resistive heating), however, thermal energy also escapes from the kettle via convection (i.e. steam and heated air leaving the kettle), conduction (with the surrounding air or the surface), and radiation.
- Since shiny objects are worse emitters, a shiny kettle reduces the amount of heat that escapes via radiation so that the water will heat up quicker and with more efficiency.

3C

- *Q* represents summer in Australia as it is the diagram where the Southern Hemisphere gets more radiation.
- *P* and *Q* are the extreme states of summer and winter in either hemisphere.
- When the Earth is halfway between these states the Northern Hemisphere and Southern Hemisphere will receive a similar amount of radiation. This is spring/autumn. This amount of radiation is less than they would receive in summer and more than in winter.

3D

- The side of the Earth that is facing the Sun would immediately (or after about 8 minutes, which is how long it takes for the Sun's radiation to reach the Earth) get hotter with the increased radiation.
- But the greenhouse effect would be responsible for causing the whole planet to warm up by trapping this heat. The increase would take time as the atmosphere needs to build up this store of energy.
- The more greenhouse gases there are in the atmosphere, the faster the atmosphere will heat up.

3E

- The climate is a useful concept because it is a measure of the long-term average weather, allowing us to predict how it will change in the future.
- The time period must be long enough such that it is not affected by random variation or the many short-term climate cycles (such as seasonal fluctuations or El Niño). 30 years is long enough for these variations to cancel out so that the measure of climate reflects the region's average weather.
- The time period must be short enough to be practical and to allow us to gauge long-term climatic trends that humans may be able to affect or prepare for.

3F

- The heat pump moves thermal energy from the cool side and expels it into the hot side. In the case of a refrigerator, this means it removes thermal energy from inside the refrigerator and expels it via coils at the back of the refrigerator.
- The heat pump does not decrease the total amount of thermal energy. It simply moves thermal energy. (In fact, it adds thermal energy due to inefficiencies). Hence, if a refrigerator door is left open, the room will stay approximately the same temperature (or increase) because the heat expelled at the back is equal to the heat removed from the front.

4A

- Milliamp (mA) is a measure of current, equal to one thousandth of an ampere (A). Hours (h) is a measure of time. Therefore, mA h is the unit representing current multiplied by time. From $I = \frac{Q}{t}$, we can rearrange this to $Q = It$ and see that mA h is a measure of charge, Q.
- Current is a measure of how fast charge is moving over time. Therefore, a higher current will mean that more charge is delivered by the battery in a given period of time. Since a mA h rating measures charge, the battery connected to the circuit drawing more current (Circuit *X*) will run out faster than the battery connected to the lower current circuit (Circuit *Y*).

4B

- In most circuits, it is not important to consider the resistance of conducting wires when conducting circuit analysis, since the magnitude of their resistance (which would usually be in the order of 10^{-4} Ω) is insignificant compared to the resistance of the circuit components. Accounting for wire resistance would cause no significant difference in analysis results.
  - If the wires were extremely long their resistance would increase, so it may become important to consider their resistance.
  - If the wires were extremely thick their resistance would decrease, so it would be even less necessary to consider their resistance.

4C

- If another bulb was added in series, the total equivalent resistance of the circuit would increase, since $R_T = R_1 + R_2 + \ldots + R_n$. With a constant voltage source, an increase in resistance would cause a decrease in current (by Ohm's law) around the series circuit. Additionally, adding a bulb will decrease the voltage drop across each individual component since $V_T = V_1 + V_2 + \ldots + V_n$ must remain true. Given that $P = VI$, and that V and I both decrease, the consequence of adding another bulb in series is a reduction in the power consumption of each bulb.
- If a bulb blew, then the circuit would be open, and there would be no path for current to flow. This means that $I = 0$ A, and given $P = VI$, the power consumption of each bulb is therefore 0 W.

4D

- If a bulb blew, one arm of the circuit would be open, however the pathways that all other bulbs are a part of remain part of a complete circuit. Therefore the remaining bulbs would remain on.
- Since each bulb is connected in parallel, removing a component does not affect the current through the individual parallel arms, even though the total current is affected. So, the power consumption of each remaining bulb does not change.

4E

- The equivalent resistance of two parallel components, when one component has a much greater resistance than the other, is approximately equal to that of the smaller resistance component. For example, with $R_1 = 10$ Ω and $R_2 = 10 \times 10^3$ Ω,
  $R_T = \left(\frac{1}{10} + \frac{1}{10 \times 10^3}\right)^{-1} = 9.99 \approx R_1$.
- For an accurate voltage measurement, we need the equivalent resistance of the component being measured and the voltmeter to be as close as possible to the resistance of the component being measured. This means that the voltmeter must have much greater resistance than the component being measured.
- Digital voltmeters typically have a resistance of around 10 MΩ, which usually satisfies the condition of being much greater than the component being measured.

5A

- In the configuration shown, no current would flow through the diode, but current can flow through the resistor since parallel arms form separate circuit loops. The circuit will behave as if the diode arm is not connected.
- When no current is flowing (like in this configuration) the voltage across the ideal diode is not limited. This means that the voltage across the diode and the resistor will be equal to the source voltage, and there will be no effect on the operation of the resistor.
- If the source were connected in the reverse direction, current would flow through the diode if the source voltage met the threshold voltage. However, an ideal diode voltage cannot exceed the threshold voltage while allowing current. Since parallel arms always have the same voltage drop, the resistor must also have a maximum voltage drop equal to the diode threshold voltage. This means that the source cannot provide a voltage higher than the threshold voltage, and that the operation of the circuit is significantly affected.

5B

- A hand saw cuts through wood by moving relative to the wood.
- It gets this kinetic energy from the hand of the person holding the saw.
- Saw teeth do not need to move from the hand to the wood. The cutting can be done by only a few saw teeth, but the back and forth motion of the hand causes all the teeth to move which provides the energy to cut through the wood.
- Energy is transformed into thermal energy (or many other forms) by charges moving through the circuit. In the case of thermal energy, the charges collide with each other and the atoms in the conductor to increase the average kinetic energy of the particles.
- This process does not require charges to move from the source to the appliance. Like the teeth on a saw, all the charges move in the circuit almost at once. This motion transfers energy without the individual charges needing to move far. The direction of motion is not important.

5C

- As long as another safety device does not cause a break in the circuit, the appliance will operate normally because the current can flow from the active wire through the appliance to the earth, which is where a neutral wire ultimately leads to as well.
- However, if an RCD is connected then it will detect a difference between the currents in the active and neutral wires and it will shut down the power on the active wire.
- This configuration poses some dangers. Firstly, the exterior of the appliance would connect to ground via the neutral wire which is a less direct/higher resistance path than the earth wire, which means it would not provide as effective protection. Secondly, since an RCD would switch off the circuit whenever it is used, a user might assume the RCD is faulty and remove it which means there is greater risk of electric shock if something else goes wrong.

6A

- Antiparticles are created in a large number of common processes like various forms of beta radiation, which produce positrons or antineutrinos. Some particles are also their own antiparticle, like the photon.
- When a particle and an antiparticle collide, they annihilate (produce energy in the form of photons). An antihydrogen atom produced at CERN would be composed of a positron orbiting an antiproton.
- A large amount of energy is required to isolate the created antimatter (keeping it stored in a constantly maintained magnetic field and a near-perfect vacuum). When these components are switched off, the antimatter annihilates with atoms in the walls of the machine they are made in. The energy of antimatter colliding with its environment is what scientists measure to prove they created antimatter.
- The massive amounts of energy required to produce antimatter and consequently to store it (and the very large associated costs) prevent a dangerous amount of antimatter from being created and stored at CERN. Despite its extremely powerful and expensive colliders, the total amount of antimatter created over CERN's history is very small – far less than would be needed to produce an explosion comparable to an atomic bomb.

6B

- The strong force holds the nucleus together and it holds quarks together to form nucleons. If the strong force did not exist, protons, neutrons, and atoms as a whole could not exist. This would mean that the universe would be composed similarly to how it was less than 10 microseconds after the Big Bang – a soup of quarks!
- The weak force is responsible for radioactive decay. If the strong force also did not exist, there would be no atoms to stabilise through radioactive decay. If the strong force still existed, but the weak force did not, there would be elements that normally decay through weak force interactions that could no longer decay. These elements (like uranium) would then be able to be handled without protection! Unfortunately, the weak force is also involved in the fusion reactions that powers the Sun, which would mean the Sun could not exist in a universe without the weak force and so life could not exist on Earth either.

6C

- 500 mL of water must flow out of the bottle for the volume to decrease by half (so that 500 mL remains). This will take 5 seconds.
- An additional 250 mL must flow out of the bottle for the volume to decrease to half of 500 mL. This will take an additional 2.5 seconds.
- The amount of time it takes for the volume to halve decreases as volume decreases (because the flow rate is constant), which means that the concept of a half-life does not apply. This differs from radioactive decay where the decay rate depends on the amount of substance remaining so that the time taken for half the substance to decay is always constant.

6D

- Blue represents nuclides that undergo beta minus decay. This is because they are to the left of the Valley of Stability (it has fewer protons compared to the nuclides on the Valley of Stability with the same mass number). Beta minus decay increases the number of protons in the nucleus without changing the mass number, making the nuclide more stable. In other words, the daughter nuclide is shifted to the right, closer to the Valley of Stability.
- Orange represents nuclides that undergo beta plus decay. This is because they are to the right of the Valley of Stability (it has more protons compared to the nuclides on the Valley of Stability with the same mass number). Beta plus decay decreases the number of protons in the nucleus without changing the mass number, making the nuclide more stable. In other words, the daughter nuclide is shifted to the left, closer to the Valley of Stability.
- Yellow represents nuclides that undergo alpha decay. These elements are so heavy that they are inherently unstable, so the emission of an alpha particle increases stability. They also contain too many protons (they are to the right of the Valley of Stability).

7A

- Stars will burn the most efficient fuel available, which is the fuel that releases the most energy per nucleon. The gradient of the binding energy curve decreases as the nuclei get bigger and so there is less energy released in a fusion reaction. Hence the most efficient fuel will be the smallest remaining element, so the star will burn increasingly large nuclei in order of size starting with hydrogen.
- Once the star reaches elements around iron and nickel, they have produced the most tightly bound nuclei possible with the greatest binding energy per nucleon. There is no possible reaction that could release enough energy to sustain the star and so they will not be able to produce elements heavier than nickel.
- In order to produce nuclei heavier than nickel through fusion, a net energy input is required. The conditions necessary to supply a sufficient amount of energy are only possible through cataclysmic events such as supernovae.

7B

- Since a laser is monochromatic (releases light with a single wavelength) the radiation it emits all has the same energy.
- The only way for a single wavelength to be generated by electron transitions is if only one transition is available – which only occurs if the electrons are moving between the first excited state and the ground state. From the energy levels diagram, this amount of energy is 10.2 eV.

- If a higher amount of energy was absorbed, corresponding to a higher energy level, electrons would have the ability to release more than one wavelength of light as they transition to the ground state. This would compromise the laser's monochromatic property.

7C

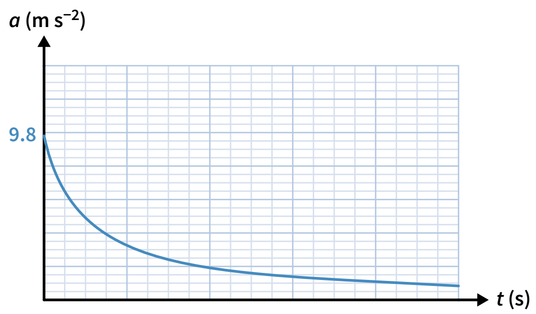
- This scenario is a hypothesised end for our Universe known as the "Big Rip".
  - Since the recessional velocity is proportional to distance, objects far enough away will be receding faster than the speed of light, which imposes a limit on the movement of objects and any emitted light through space, but not the expansion itself. The space between us and a distant object could be expanding faster than any emitted light can cover this distance.
  - The light from such objects will never reach Earth, regardless of how powerful a telescope or how long we look for. Hence, objects far enough away will never be seen by Earth (all the objects which emit light that will eventually reach Earth encompasses the observable Universe).
  - If Hubble's constant was increasing, the distance required for objects to be receding from us faster than light would be decreasing. Therefore the boundaries of the observable Universe would be shrinking. Eventually, our observable Universe would consist only of the nearby bodies bound together by gravity.

8A

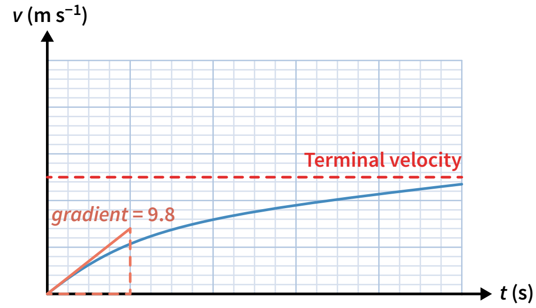
- By 'faster' it is meant that the acceleration of the sports car is greater than that of the truck. With a greater acceleration, the sports car reaches the maximum speed before the truck does, which means it moves ahead of the truck and reaches the next set of lights first.

8B

- Initially, the magnitude of acceleration would be at, or near, 9.8 m s^{-2}. The longer the basketball has fallen for, the greater the effects of air resistance will be and therefore the more the magnitude of acceleration will decrease.
- This will mean that the change in velocity from one second to the next will get progressively smaller over time as the ball approaches terminal velocity.
- At some point, the change in velocity will reach 0, at which point the velocity will be constant and we would say that the basketball has reached terminal velocity.
- We would expect the acceleration-time graph to therefore look something like this:



- Since acceleration at a point in time is equal to the gradient of the velocity-time graph at that point, the velocity-time graph should initially increase at roughly 9.8 m s^{-2} then flatten out towards horizontal as it approaches the terminal velocity.



8C

- As the word falls, the letters will stretch vertically. The velocities of water drops at the bottom of the word will be larger than that of those towards the top, since they have been falling for a longer period of time.
- This means that for every second that passes, the lower drops will fall a greater distance, which in turn causes the word to stretch.
- Specifically, the bottom portions of each letter will stretch out more than the upper portions. This is because the relationship between displacement and time is quadratic, as is shown in the constant acceleration equation $s = ut + \frac{1}{2}at^2$ (initial velocity and acceleration are constant and equal for all of the water drops).

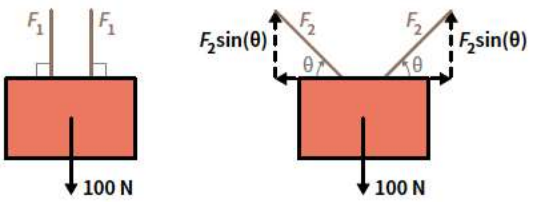
Image: ArtDesign Illustration/Shutterstock.com

9A

- When a car is accelerating, there must be a net force acting on the car in the direction it is accelerating. Therefore, the forward force on the car by the road must be greater in magnitude than any resistive forces pushing the car backwards (such as air resistance).
- When a car is not accelerating, the net force on the car is zero. This is true even if the car is in motion, which is a conclusion of Newton's 1st law. This means that the forward force on the car by the road must be equal in magnitude to any resistive forces.
- According to Newton's 3rd law, there must be a friction force directed backwards on the road by the car since there is a force directed forwards on the car by the road. The magnitude of the friction force on the road by the car will be the same as the magnitude of the forward force on the car by the road.

9B

- Whilst the strings in the first situation only have a vertical component of force, the strings at 45° have both vertical and horizontal components.
- As the 100 N force acts vertically downwards, only the vertical components of the force from both situations will act to balance it.
- The horizontal component of the forces through the 45° strings only act to cancel each other out such that the mass does not accelerate from side to side. Therefore the 45° strings have an additional horizontal force component that the vertical strings do not have, meaning that they must provide a larger total force.
- Hence the 45° strings are more likely to break.

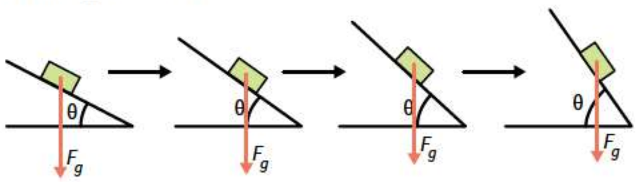


For the vertical strings:
$F_{net} = 0 \therefore F_1 + F_1 - 100 = 0$
$2 \times F_1 = 100$
$F_1 = 50$ N

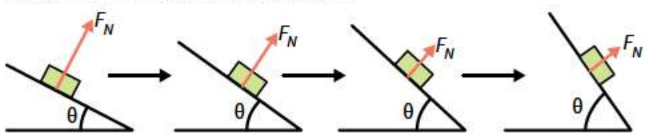
For the diagonal strings, considering the vertical component:
$F_{net} = 0 \therefore F_2\sin(45°) + F_2\sin(45°) - 100 = 0$
$2 \times F_2\sin(45°) = 100$
$F_2 = 71$ N

9C

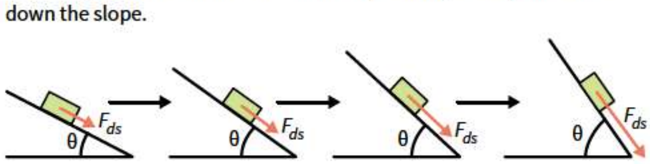
a The magnitude of the force due to gravity remains constant as the angle is increased. The direction of the force due to gravity remains constant as the angle is increased.



b The magnitude of the normal force decreases as the angle is increased as the value of cos(θ) decreases. The direction of the normal relative to the horizontal does change as the angle increases, because the normal force always acts perpendicular to the slope.



c The magnitude of the force down the slope increases as the angle is increased as the value of sin(θ) increases. The direction of the force down the slope relative to the horizontal does change as the angle increases, because the force down the slope always acts parallel and down the slope.



9D

- When lifting something heavy, the force due to gravity will act vertically downwards at the shoulders and cause a torque at the pivot point, the lower back. The distance between the point of rotation and where the force is applied is the same in both scenarios, however the angle of application of the force to our back is smaller when lifting with the knees. This means that the component of the force acting perpendicular to the back will be smaller.

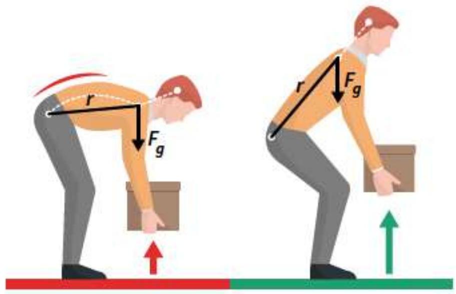


Image: elenabsl/Shutterstock.com

Knowing that $\tau = rF\sin(\theta)$, the magnitude of the torque will decrease as the value of θ decreases. Hence a decrease in the angle when bending the knees results in a smaller torque acting at the lower back despite the force and distance from the pivot point remaining the same. This results in lifting with the knees being safer than when lifting with the back.

9E

- As the system wants to preserve the state of equilibrium, the reaction forces on the pencil from each finger need to be the same. To allow this to happen the centre of mass of the pencil needs to be halfway between the fingers at all times. This rule means that the frictional forces change as you move your fingers to keep the centre of the pencil in between your fingers.
- This would be the same if the pencil was imbalanced with a weight, however the centre of mass would no longer be at the centre of the object. The fingers would instead be equally spaced around a point further up the pencil towards the mass.

10A

- In all situations the change in momentum of Alex's head will be the same, and therefore the impulse will be the same.

  a When not wearing a helmet, Alex's head will decelerate and change momentum very quickly.
  By the equation $I = F\Delta t$, there will be a very large force on Alex's head when not wearing a helmet.

  b When wearing a bicycle helmet, the time Alex's head takes to decelerate will be greatly increased.
  By the equation $I = F\Delta t$, there will be a greatly reduced force on Alex's head when wearing a helmet compared to when not wearing a helmet.

  c When wearing a concrete helmet, Alex's head will decelerate and change momentum very quickly in a similar fashion to not wearing a helmet.
  By the equation $I = F\Delta t$, there will be a very large force on Alex's head when wearing a concrete helmet.

10B

- If the machine can run forever once it has been started, then this would mean that it does not lose any useful energy. The useful energy in would always equal to the useful energy out.
- This would require 100% energy efficiency. This is not physically possible, since in reality the existence of friction will always cause useful energy to be made unrecoverable. It is also impossible to create a surface that is perfectly frictionless.

10C

- If the Moon were to move away from the Earth, we would expect it to slow down. As it moves away from the Earth, it will convert kinetic energy to gravitational potential energy as energy is always conserved. This would decrease its speed.
- If the Moon were to move closer to the Earth, we would expect it to speed up. As it moves towards the Earth it will convert gravitational potential energy to kinetic energy as energy is always conserved. This would increase its speed.

10D

- A shorter and stiffer rubber band will have a larger spring constant, k, than one which is large and stretchy. However, the stiffer rubber band will not be able to be stretched as far as the larger rubber band so it will have a smaller Δx value.
- Knowing that the equation for strain potential energy is $SPE = \frac{1}{2}k(\Delta x)^2$, by increasing the spring constant we will increase *SPE* in a linear manner and by increasing the extension we will increase *SPE* in a quadratic manner.
- The maximum speed will be achieved when the kinetic energy, $\frac{1}{2}mv^2$, of the rubber band is a maximum. As the rubber band is released, the energy stored as strain potential energy is transformed into kinetic energy, so a maximum strain potential energy is desired.
- As *SPE* is proportional to both the extension and the spring constant, the preferred rubber band is one with a combination of a large spring constant and large extension, not just one of these features.

GLOSSARY

A

AC (alternating current) electricity electricity with a periodically alternating direction of current and voltage p. 192

acceleration the rate of change of velocity per unit time (vector quantity) p. 286

accuracy a relative indicator of how well a measurement agrees with the 'true' value of a measurement p. 13

active wire the wire at the end of an AC electrical system with a varying potential; this wire connects to the voltage supply p. 192

activity (radiation) the rate of radioactive decays per unit of time p. 234

albedo a measure of how much shortwave radiation is reflected by the Earth or by a particular surface p. 105

alpha decay the process by which an unstable nucleus decays into a more stable nucleus by emitting an alpha particle p. 240

alpha particle a particle composed of two protons and two neutrons (the nucleus of a standard helium atom) p. 240

angular acceleration the rate of change of angular velocity per unit time p. 361

angular velocity the rate of rotation per unit time p. 361

antiparticle a particle with the same mass and spin as its corresponding particle but with opposite charge and other quantum numbers (such as baryon number, lepton number, and strangeness) p. 218

atmosphere the layers of gases around a planet p. 93

average acceleration the average rate of change of velocity per unit time over a given period (vector quantity) p. 298

average velocity the average rate of change of displacement per unit time over a given period (vector quantity) p. 298

B

baryon a subatomic particle made up of an odd number of quarks (typically 3), such as a proton or a neutron p. 218

beta minus decay the process by which an unstable nucleus decays into a more stable nucleus by transforming a neutron into a proton and emitting an electron and an antineutrino p. 240

beta particle an electron (beta minus decay) or a positron (beta plus decay) p. 240

beta plus decay the process by which an unstable nucleus decays into a more stable nucleus by transforming a proton into a neutron and emitting a positron and a neutrino p. 240

binding energy the total energy required to split a nucleus into its constituent nucleons p. 252

black body an ideal body that absorbs (before re-emitting) all incoming electromagnetic radiation and does not transmit or reflect any of the radiation p. 83

boil convert from liquid to gas at a certain temperature and pressure p. 59

C

charge a fundamental property of subatomic particles responsible for electric interaction p. 136

charge carrier a charged particle that contributes to an electric current p. 136

circuit breaker a safety device that opens a resettable switch, causing a break in an electric circuit, when too much current flows through it p. 200

climate the long-term (minimum 30 years) average weather of a planet or region p. 105

collision the coming together of two or more objects where each object exerts a force on the other p. 374

composite particle a particle that is composed of two or more elementary particles p. 218

compression the process of decreasing an object's length p. 402

condense convert from gas to liquid at a certain temperature and pressure p. 59

connected bodies two or more objects either in direct contact or attached by a string, rope, cable or similar connection p. 340

controlled variable a variable that has been held constant in an experiment in order to test the relationship between the independent and dependent variables p. 2

convection the transfer of heat through the bulk movement of matter p. 47

convection cell a circular flow of fluid caused by differences in temperature and hence fluid densities p. 47

conventional current the direction of flow of positive charge p. 136

core the dense, hot, molten centre of the Earth p. 93

crust the thin surface of the Earth made of solid mineral and rock p. 93

current (electric) the rate of movement of charge with respect to time requiring the movement of charged particles p. 136

curve of best fit a curved line that indicates the relationship between the independent and dependent variables on a graph. It must pass through the uncertainty bars of all data points p. 21

D

DC (direct current) electricity electricity with a constant direction of current and voltage p. 192

density mass per unit volume; a measure of how closely packed matter is p. 47

dependent variable a variable that the experimenter measures, which is predicted to be affected by the independent variable. Dependent variables are plotted on the vertical axis of graphs p. 2

diode a semiconductor device which limits current flow to one direction p. 182

direct current (DC) electric current that flows in a constant direction p. 136

discrete limited to certain values (not continuous) p. 260

displacement the change in position of an object, or the shortest path (including direction) between the initial and final positions (vector quantity) p. 286

distance the total length of a given path between two points (scalar quantity) p. 286

E

earth wire the third wire that connects to household appliances, which provides a low-resistance path for current to flow from the outside of the appliance to the ground in order to avoid an electric shock p. 200

electric potential energy potential energy due to the separation of charge p. 136

electric shock the sensation and damage done when electric current flows through a person or other living thing p. 200

electromagnetic radiation a disturbance in the electric and magnetic fields (electromagnetic fields) of charged particles; includes visible light p. 47

electromagnetic spectrum the range of all electromagnetic waves ordered by frequency and wavelength p. 78

electromagnetic wave a disturbance in the electric and magnetic fields (electromagnetic fields) of charged particles; includes visible light p. 78

elementary particle a particle that is not made up of other particles p. 218

emissivity a measure of how effectively an object emits radiation p. 83

energy a quantity describing the ability to cause a physical change (scalar) p. 40

enhanced greenhouse effect the magnification of the greenhouse effect due to increased greenhouse gas levels that are a result of human activity p. 105

equilibrium the state of a system when it is in both translational and rotational equilibrium p. 361

equivalent resistance the effective resistance when two or more resistive components are treated as one component p. 156

error the difference between a measured value and its 'true' value p. 13

evaporate convert from liquid to gas only at the liquid's surface due to high-energy particles in the liquid escaping p. 59

extension the process of increasing an object's length p. 402

F

feedback where a change is amplified (positive feedback) or suppressed (negative feedback) due to the effects of that change p. 105

first law of thermodynamics law that states that the change in internal energy of a system is equal to the heat transferred to it and the work done on it p. 68

fluid a substance that flows easily; a liquid or gas p. 47

force a push or a pull with an associated magnitude and direction (vector quantity) p. 322

fossil fuel a material that started as living organisms and has transformed into an energy-dense fuel as a result of geological processes over millions of years. Examples include coal, oil, and gas p. 115

freeze convert from liquid to solid at a certain temperature and pressure p. 59

frequency the number of cycles completed per unit time p. 78

friction a force that resists the relative motion of two surfaces which are in contact p. 340

fundamental forces the four forces that cannot be broken down into other forces: the gravitational force, the electromagnetic force, the strong force, and the weak force p. 228

fuse (electric) a safety device that melts, causing a break in an electric circuit, when too much current flows through it p. 200

G

gamma decay the process by which an excited nucleus decays into a more stable nucleus by emitting energy in the form of gamma rays p. 240

gamma rays high energy photons p. 240

gradient the graphical representation of the rate of change of one variable with respect to another p. 28

gravitational force the force experienced by an object due to the gravitational field of another object p. 322

gravitational potential energy the stored energy associated with the position of an object in a gravitational field p. 394

greenhouse effect the trapping of thermal radiation emitted from the Earth by greenhouse gases in the atmosphere, keeping the Earth's temperature higher than it would otherwise be p. 99

greenhouse gas a gas that is better at absorbing radiation emitted by the Earth than radiation emitted by the Sun p. 99

H

hadron a subatomic particle made up of two or more quarks held together by the strong force p. 218

half-life the time it takes for half of a radioactive sample to decay p. 234

heat energy that is flowing between systems due to a difference in temperature p. 47

human error see personal error p. 13

hypothesis a proposed explanation that predicts a relationship between variables and can be tested through experimentation p. 2

I

ideal spring a spring that obeys Hooke's law so that the force it exerts is proportional to its change in length p. 402

impulse the change in momentum of a body as the result of a force acting over a time (vector) p. 374

inclined plane a flat surface that is at an angle to the horizontal plane p. 340

independent variable the variable that the experimenter manipulates (selects or changes), which is predicted to have an effect on the dependent variable. Independent variables are plotted on the horizontal axis of graphs p. 2

inflation a very short time in which the early universe underwent extremely rapid expansion p. 267

instantaneous acceleration the rate of change of velocity per unit time at a single instant in time (vector quantity) p. 298

instantaneous velocity the rate of change of displacement per unit time at a single instant in time (vector quantity) p. 298

internal energy the total energy associated with the random motion of particles and the interactions between the particles within a system p. 40

internal resistance the inherent resistance associated with an electric power source p. 182

ionisation energy the energy required to remove an electron from an atom p. 240

ionising power the ability of a given type of radiation to cause another atom to lose electrons and become an ion p. 240

isolated system a collection of interacting objects for which there is no external exchange of mass and energy p. 374

isotope an atom of an element that has the same number of protons but a different number of neutrons compared to another atom of the element p. 228

K

kinetic energy the energy associated with the motion of an object p. 40

L

latent heat the heat absorbed or released to change the state of a substance p. 59

light-dependent resistor a variable resistor that decreases resistance as the intensity of light hitting its sensitive surface increases p. 182

light-emitting diode a diode that emits light when a potential difference is applied p. 182

line of best fit a straight line that indicates the relationship between the independent and dependent variables on a graph. It must pass through the uncertainty bars of all data points p. 21

linearise the process of transforming data through mathematical operations so that, when graphed, a line of best fit can be drawn through the data p. 21

live wire see 'active wire' p. 192

M

magnitude the size or numerical value of a quantity without sign (positive or negative) or direction p. 8

mantle a solid region under the surface of the Earth between the crust and the outer core p. 93

mass defect the difference in mass between a nucleus and its constituent nucleons p. 252

medium the physical substance through which energy (e.g. heat or sound) travels p. 47

melt convert from solid to liquid at a certain temperature and pressure p. 59

meson a subatomic particle made up of one quark and one antiquark p. 218

model (scientific) a representation of a physical process that cannot be directly experienced p. 2

momentum a quantity of a body in motion which is equal to the mass of the body multiplied by its velocity (vector) p. 374

N

natural length the length of a spring when no external forces are acting on it p. 402

net force the vector sum of all forces acting on an object p. 322

neutral wire the wire at the end of an AC electrical system that is fixed at zero volts; this wire connects to the ground p. 192

Newton's first law law that states an object will accelerate only if a non-zero net force (unbalanced force) acts upon it p. 322

Newton's second law law that states the acceleration of an object is equal to the net force applied divided by the mass of the object being accelerated p. 322

Newton's third law law that states that for every force there is a reaction force of equal magnitude and opposite direction p. 322

node (electric) a point in a circuit where multiple components are connected together p. 163

non-renewable energy source an energy source that is not replaced or that is replaced at a slower rate than it is being used p. 115

normal force the contact force that acts between two objects with equal magnitude on each object and at right angles to the contact surfaces p. 322

nuclear fission the process of splitting a single nucleus into several smaller nuclei p. 252

nuclear fusion the process of forcing several smaller nuclei together to form a single large nucleus p. 252

nucleon a proton or a neutron p. 218, 228

nuclide a nucleus with a specific number of neutrons and protons p. 240

O

observation the acquisition of data using senses such as seeing and hearing or with scientific instruments p. 2

ohmic device a device that has a constant resistance for all voltages, meaning it follows a linear I-V relationship p. 148

P

parallel circuit an electric circuit that has only parallel connections p. 163

parallel connection an arrangement where multiple components connect the same two points so there are multiple alternative pathways for current to flow p. 163

particle a small, discrete object or portion of matter p. 40

particulates small, distinct solids such as dust or soot that are suspended in a liquid or gas p. 115

peak wavelength the wavelength of the highest intensity electromagnetic wave released as thermal radiation p. 83

penetrating power an indicator of the extent to which a given type of radiation can penetrate matter before it loses its energy p. 240

personal error mistakes in an experiment's design, execution or analysis caused by a lack of care that negatively impact or invalidate the conclusions of an experiment p. 13

potential difference the amount of electric potential energy per unit charge between two points p. 136

potential energy the energy associated with the position of an object in the presence of a force that could move the object p. 40

potentiometer a variable resistor that changes resistance depending on the manual control of a sliding contact p. 182

power the rate of change of energy with respect to time p. 83, 136

precision a relative indicator of how closely different measurements of the same quantity agree with each other p. 13

product a substance that is formed as the result of a reaction p. 252

Q

qualitative data data that cannot be described by numerical values p. 2

quantitative data data that can be described by numerical values p. 2

quarks elementary particles that can combine to form hadrons p. 218

R

radiation any type of energy, or energy-carrying particles, that spreads as it travels away from a source p. 218, 240

radioactive decay the process of an atom becoming more stable by losing energy and emitting particles or photons p. 228

radioisotope an isotope that will undergo radioactive decay p. 228

random error the unpredictable variations in the measurement of quantities p. 13

reactant a substance present at the start of a reaction and is involved in the reaction p. 252

recessional velocity the rate at which an astronomical object is moving away from an observer p. 267

redshift where electromagnetic waves undergo an increase in wavelength p. 267

reliability a qualitative description of how likely it is that another experimenter can perform an experiment and find the same results within a small range p. 13

renewable energy source an energy source that is constantly replaced at a greater rate than it is being used p. 115

repeatability the closeness of agreement of results when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same lab) p. 13

reproducibility the closeness of agreement of results when an experiment is repeated by a different experimenter under slightly different conditions (using their own equipment and lab) p. 13

residual current device (RCD) a safety device that switches off a household electric circuit when it detects a difference between the current flowing in the active and neutral wires p. 200

resistance (electrical) a measure of an object's opposition to the flow of electric current p. 148

resistivity (electrical) a property of a material describing how much it opposes the flow of electric current p. 148

resistor an electrical component that resists the flow of electric current and causes a drop in voltage p. 148

RMS (root-mean-square) a measure of a time-varying (such as AC) voltage or current. A constant DC voltage or current with the same value as the RMS would deliver the same average power p. 192

rotational equilibrium the state of a system when the torques on the system sum to zero p. 361

S

scalar quantity a quantity that has only magnitude (size) p. 286

series circuit an electric circuit that has only series connections p. 156

series connection a connection of components from end to end p. 156

short circuit a situation in which current skips part of a circuit by following an unintended path with very low resistance, causing a larger current to flow p. 200

SI unit the accepted standard unit used for measuring a quantity. It is an abbreviation of "le Système international d'unités" p. 8

significant figures all digits quoted starting with the first non-zero digit giving an indication of the confidence in a measurement p. 8

specific heat capacity the heat per unit of mass needed to increase the temperature of a substance by one kelvin (or degree Celsius) p. 59

specific latent heat of fusion the heat per unit of mass needed to convert a given substance from a solid into a liquid p. 59

specific latent heat of vaporisation the heat per unit of mass needed to convert a given substance from a liquid into a gas p. 59

speed the rate of change of distance per unit time (scalar quantity) p. 286

spring constant a value that describes the stiffness of a spring p. 402

state of matter the physical property of an object being either a solid, liquid, or a gas p. 40

strain potential energy the energy stored by the deformation of an object; also known as elastic potential energy or spring potential energy p. 402

strong force the fundamental force that holds quarks together to form nucleons and that holds nucleons together within the nucleus p. 228

synchrotron a machine for accelerating charged particles to a great speed in order to release electromagnetic radiation p. 260

system a collection of interacting particles or objects that are treated as a single entity p. 40

systematic error a consistent, repeatable deviation in the measured result from the actual results, often due to a problem with the experimental design or calibration of equipment p. 14

T

tangent a line which touches, but does not cross, a curve at a single point p. 260

tectonic plate a large portion of the Earth's crust, also known as a lithospheric plate p. 93

temperature a measure of the average translational kinetic energy of the particles in a system (scalar) p. 40

tension a pulling or stretching force that acts through an object connecting two bodies; the magnitude of the force on both bodies is the same p. 340

theory (scientific) an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation p. 2

thermal conduction the transfer of heat through direct contact p. 47

thermal energy see 'internal energy' p. 40

thermal equilibrium the state of two (or more) systems having the same temperature so that there is no net flow of thermal energy from one system to the other p. 40

thermal radiation the transfer of heat in the form of electromagnetic radiation p. 47

thermistor a variable resistor that changes resistance with temperature p. 182

torque the turning effect caused by a force at a distance from a pivot point (vector) p. 352

transducer a component or device that transforms energy between different forms p. 182

translational equilibrium the state of a system when the forces on the system sum to zero p. 361

trendline see line of best fit or curve of best fit p. 21

U

uncertainty the qualitative appraisal of how well an experiment measures what it is intended to measure p. 14

V

vacuum a region that does not contain matter p. 47

validity the quality of an experiment measuring what it intends to measure p. 14

vector quantity a quantity that has both magnitude (size) and direction p. 286

velocity the rate of change of displacement per unit time (vector quantity) p. 286

volatile the property of changing between the liquid state and the gaseous state easily p. 115

voltage see potential difference p. 136

voltage divider a resistive circuit that outputs a voltage smaller than its input voltage p. 182

W

wavelength the distance between two identical points in a wave p. 78

weak force the fundamental force responsible for beta decay by changing the flavour of a quark p. 228

weather the state of the atmosphere at a particular time p. 105

work the change in energy caused by a force displacing an object in the direction it is acting in p. 385

Z

zeroth law of thermodynamics law that states that if two systems are each in thermal equilibrium with a third system, then they are also in thermal equilibrium with each other p. 70

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FORMULAS IN THIS BOOK

1E	gradient of a straight line	$gradient = \frac{y_2 - y_1}{x_2 - x_1}$
2B	heat flow rate for conduction	$\frac{Q}{t} \propto \Delta T$
2C	heat needed to increase temperature	$Q = mc\Delta T$
2C	heat needed to change state	$Q = mL$
2D	work done	$W = Fs$
2D	change in internal energy	$\Delta U = Q + W$
2D	internal energy change due to temperature change	$\Delta U = mc\Delta T$
3B	Wien's Law	$\lambda_{max} = \frac{b}{T}$
3B	Stefan-Boltzmann Law	$\frac{P_f}{P_i} = \frac{T_f^4}{T_i^4}$
4A	potential difference	$V = \frac{E}{Q}$
4A	electric current	$I = \frac{Q}{t}$
4A	power	$P = \frac{E}{t}$
4A	electric power	$P = VI$
4B	resistance	$R = \rho \frac{L}{A}$
4B	Ohm's law	$V = IR$
4C	equivalent series resistance	$R_T = R_1 + R_2 + \ldots + R_n$
4D	equivalent parallel resistance	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
5A	voltage divider equation	$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$
5B	RMS voltage	$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$
5B	RMS current	$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$
6C	radioactive nuclei remaining	$N = N_0 \left(\frac{1}{2}\right)^n$
6C	activity	$A = A_0 \left(\frac{1}{2}\right)^n$
7A	mass-energy equivalence	$E = mc^2$
7A	conversion of mass-energy	$\Delta E = \Delta mc^2$
7B	energy released as electromagnetic radiation due to electron transitions	$E_{released} = \Delta E$
7C	Hubble's law	$v = H_0 d$

8A	average speed	$speed = \frac{distance}{time}$
8A	average velocity	$v_{avg} = \frac{\Delta s}{\Delta t}$
8A	average acceleration	$a_{avg} = \frac{\Delta v}{\Delta t}$
8C	constant acceleration equations	$v = u + at$ $s = \frac{1}{2}(u + v)t$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$
9A	Newton's second law	$F_{net} = ma$
9A	force due to gravity	$F_g = mg$
9C	force down a slope	$F_{ds} = mg\sin(\theta)$
9D	torque	$\tau = r_{\perp} F$
10A	momentum	$p = mv$
10A	conservation of momentum	$\Sigma p_i = \Sigma p_f$
10A	impulse	$I = \Delta p = m\Delta v$ $I = F\Delta t$
10B	kinetic energy	$KE = \frac{1}{2}mv^2$
10B	work done	$W = Fs$
10B	power	$P = \frac{E}{t}$
10B	efficiency	$\eta = \frac{useful\ energy\ out}{total\ energy\ in}$
10C	change in gravitational potential energy	$\Delta GPE = mg\Delta h$
10C	final speed of an object moving in a gravitational field	$v = \sqrt{-2g\Delta h + u^2}$
10D	Hooke's Law	$F_s = -k\Delta x$
10D	strain potential energy	$SPE = \frac{1}{2}k(\Delta x)^2$