Edrolo

VCE PHYSICS

Units 3 & 4

2ND EDITION

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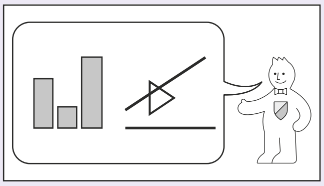
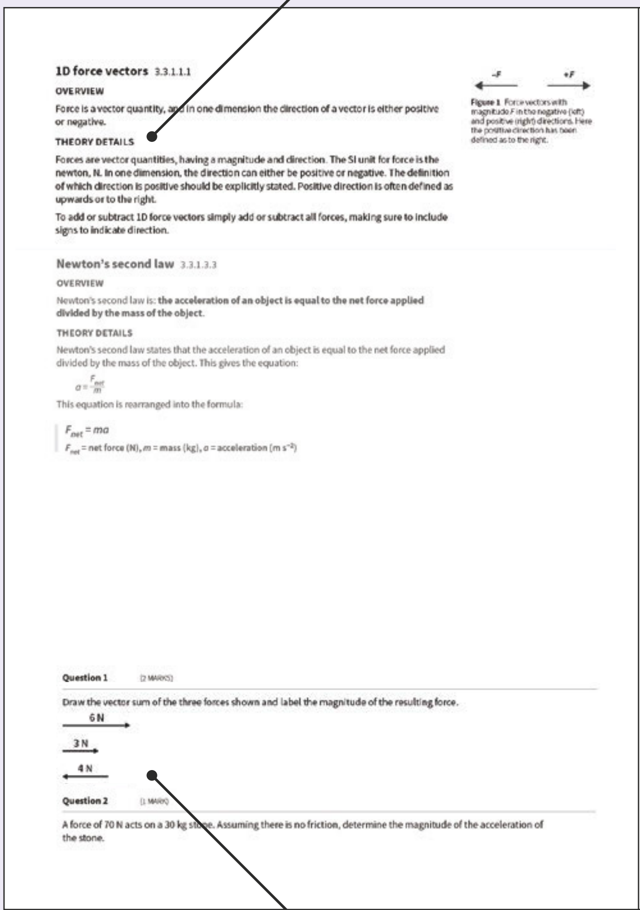
Each lesson in this book has a corresponding online video that further unpacks each and every concept.




1D force vectors 3.3.1.1

OVERVIEW

Force is a vector quantity, and in one dimension the direction of a vector is either positive or negative.

THEORY DETAILS

Forces are vector quantities, having a magnitude and direction. The SI unit for force is the newton, N. In one dimension, the direction can either be positive or negative. The definition of which direction is positive should be explicitly stated. Positive direction is often defined as upwards or to the right.

To add or subtract 1D force vectors simply add or subtract all forces, making sure to include signs to indicate direction.

Figure 1 Force vectors with magnitude F in the negative (left) and positive (right) directions. Here the positive direction has been defined as to the right.

Newton's second law 3.3.1.3

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 rearranged into the formula:

$F_{net} = ma$

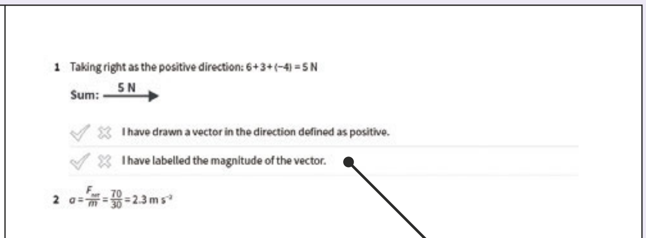
F_{net} = net force (N), m = mass (kg), a = acceleration (m s^{-2})

Question 1 (2 MARKS)

Draw the vector sum of the three forces shown and label the magnitude of the resulting force.

Question 2 (1 MARK)

A force of 70 N acts on a 30 kg stone. Assuming there is no friction, determine the magnitude of the acceleration of the stone.


1 Taking right as the positive direction: 6 + 3 + (−4) = 5 N

Sum: 5 N

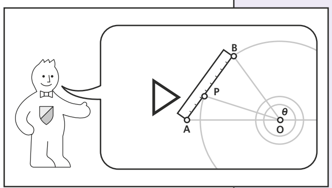
I have drawn a vector in the direction defined as positive.

I have labelled the magnitude of the vector.

2 $a = \frac{F_{net}}{m} = \frac{70}{30} = 2.3$ m s^{-2}

ANSWERS

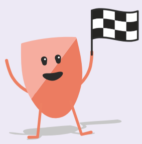
Every exam-style question in this book has an even more detailed solution video, that shows you how to break down the question, and learn all the steps required to solve it. There are also online static worked solutions and interactive checklists.



QUESTIONS

There are hundreds of questions in this book, and these questions can also be found and completed online. Answering your textbook questions online will enable you to better track your progress, and will enable your teacher to engage with your responses – so they support you even further.

Need help? Email our school support team at: help@edrolo.com.au.



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 4 AOS 3. To do this, we will examine the key knowledge dot points related to Unit 4 AOS 3 in combination with the key science skills outlined in the study design.

Key knowledge

- independent, dependent and controlled variables
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (gravity, magnetism, electricity, Newton's laws of motion, waves) and/or the construction and evaluation of a device; precision, accuracy, reliability and validity of data; and the identification of, and distinction between, uncertainty and error
- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of uncertainty and error, and limitations of data and methodologies
- models and theories, and their use in organising and understanding observed phenomena and physics concepts including their limitations
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the conventions of scientific report writing and scientific poster presentation, 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: inanimate matter and energy. This lesson will explain the scientific method as a process of seeking explanations to questions by testing predictions involving different variables.

Study design key knowledge dot points

- independent, dependent and controlled variables
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (gravity, magnetism, electricity, Newton's laws of motion, waves) and/or the construction and evaluation of a device; precision, accuracy, reliability and validity of data; and the identification of, and distinction between, uncertainty and error
- models and theories, and their use in organising and understanding observed phenomena and physics concepts including their limitations

Study design 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	4.3.3.1
Variables	4.3.1.1 & 4.3.3.8
Theories and models	4.3.6.1

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 4.3.3.1

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 (indicated 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.

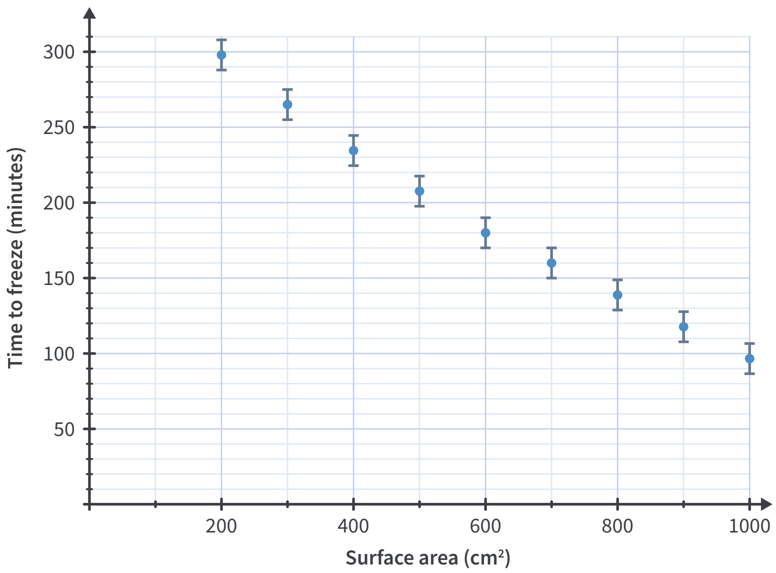


Figure 1 A graphical representation of the data from Table 1

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 4.3.1.1 & 4.3.3.8

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. Note that 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.

Theories and models 4.3.6.1

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.

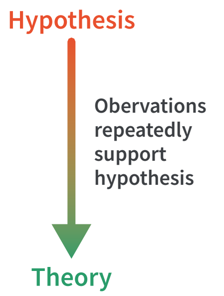


Figure 2 The progression of a possible explanation from a hypothesis to a theory

THEORY DETAILS

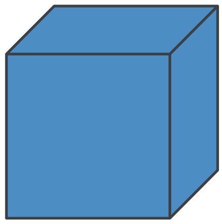
When the predictions made by a hypothesis have been tested many times, and the results consistently support the hypothesis, then the scientific community will consider the hypothesis to be true with a high degree of confidence. At this point, the explanation is now considered a scientific theory.

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. 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 (and which we will study in chapter 5 since it makes very accurate predictions in most situations). However, Albert Einstein developed an alternative explanation which has been shown to make correct predictions even in the situations where Newton's explanation failed. 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 field models for gravity, electricity, and magnetism; and wave and particle models for light and matter.

(a)



(b)

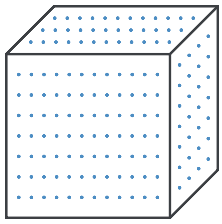


Figure 3 **(a)** Our brains model solid objects as continuous matter but **(b)** if we draw the locations of where the matter is concentrated, we see the object is mostly empty space. This diagram is not to scale.

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
https://youtu.be/6FvSXI2iBcA

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

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

1A Questions

THEORY REVIEW QUESTIONS

Question 1

A student proposes the following statement as a hypothesis: 'The time taken for a ball to fall from a height of 1.0 metre is 1.0 second.'

Which of the following best explains why this is a bad hypothesis?

A It is incorrect.

B It does not provide an explanation or predicted relationship between variables.

C It does not make a prediction.

D It does not start with 'It is predicted that…'

Question 2

For each of the following concepts relating to thermal physics, choose whether it is best described as a scientific theory, a scientific model, or an observation/measurement.

a A glass of water has a temperature of 18°C.

b Heat flows from hot objects to cold objects.

c Temperature is a measure of the average translational kinetic energy of the particles in a region.

Question 3

For each of the following three descriptions, choose whether it best describes an independent variable (IV), dependent variable (DV), or a controlled variable (CV).

a A variable which is observed and measured.

b A variable which is intentionally kept constant.

c A variable which is intentionally and directly changed.

Question 4

What is true about a scientific model? Select all that apply.

A A scientific model is always correct.

B A scientific model can correctly represent physical processes in certain situations.

C A scientific model is never correct.

D A scientific model provides a simplification of something that cannot be directly experienced.

Question 5

For each of the following variables, choose whether it is better described by quantitative data or qualitative data.

a The brand of tennis ball dropped from a height

b The height from which a ball is dropped

c The electric current flowing through a resistor

d The material from which a parachute is made

e The spring force applied to a block

EXAM-STYLE QUESTIONS

This lesson

Question 6 (7 MARKS)

Students conduct an experiment in which they drop balls with varying masses from a fixed height with an initial speed of zero and they measure the time it takes for the ball to reach the ground.

a Identify the independent variable in this experiment. (1 MARK)

b Identify the dependent variable in this experiment. (1 MARK)

c Identify the two controlled variables in this experiment. (2 MARKS)

d The students then conduct a second experiment where they drop the same ball from a variety of heights, and they use a radar gun to measure the speed of the ball just before it hits the ground.

For this second experiment, identify the **new** independent variable, dependent variable, and controlled variable. (3 MARKS)

Adapted from 2017 VCAA Exam Section B Q9b

Question 7 (1 MARK)

Which one of the following best describes a hypothesis?

A An explanation that has been rigorously tested and considered to be correct with a high level of confidence

B A true statement

C An explanation that can be tested and needs supporting evidence to be considered true

D A representation that helps to make concepts easier to understand

Adapted from 2017 VCAA Exam Section A Q19

Question 8 (1 MARK)

Which one of the following best describes a scientific theory?

A An explanation that has been rigorously tested and considered to be correct with a high level of confidence

B A true statement

C An explanation that can be tested and needs supporting evidence to be considered true

D A representation that helps to make concepts easier to understand

Question 9 (1 MARK)

Which one of the following best describes a scientific model?

A An explanation that has been rigorously tested and considered to be correct with a high level of confidence

B A true statement

C An explanation that can be tested and needs supporting evidence to be considered true

D A representation that helps to make concepts easier to understand

Question 10 (2 MARKS)

Students plan to conduct an experiment to determine the effect of slope angle on the final speed of a cart with a fixed mass. They intend to release the cart from the top of the slope, which has a fixed length, and use a radar gun to record the speed at the bottom.

Write a hypothesis for this investigation using an ‘If...then... when…’ statement.

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 key knowledge dot point

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

Study design key science skills dot point

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

Key knowledge units

Units of measurement	4.3.9.1
Significant figures	4.3.9.2

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 the digits in a measurement that are confidently known

Units of measurement 4.3.9.1

OVERVIEW

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

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 by 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 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 kelvin, candela, and mole will not be used in VCE Physics Units 3/4.

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	s A
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	$kg\ s^{-2}\ A^{-1}$

Velocity and acceleration do not have their own dedicated SI units. Instead they each use an equivalent base SI unit. These units are required knowledge for VCE Physics.

Table 3 The equivalent base SI units for velocity, or speed, and acceleration

Quantity	Equivalent base SI units
Velocity	$m\ s^{-1}$
Acceleration	$m\ s^{-2}$

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}

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.

Examples:

9.0 pm = 9.0×10^{-12} m

3 Ms = 3×10^{6} s

2.3×10^{5} mJ = 2.3×10^{2} J

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 4.3.9.2

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 number 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 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.

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 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.

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).

$$\overset{n=6}{5600000} \longleftrightarrow \overset{n=6}{5.6 \times 10^6}$$

$$\overset{n=-4}{0.00043} \longleftrightarrow \overset{n=-4}{4.3 \times 10^{-4}}$$

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)

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.

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.

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.

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 rules:
  - 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 400

b 7

c 300.20

d 5.98×10^8

e 00345.2

f 1.00034

g 0.0045678

h 0.4500

i 3.00×10^{-6}

Question 2

Write the following numbers in scientific notation.

a 3000 (accurate to 2 significant figures)

b 2 600 000 (accurate to 2 significant figures)

c 59 800 (accurate 3 significant figures)

d 0.24

e 0.00045

f 0.000000060

Question 3

Compute the following mathematical results following correct significant figure conventions.

a 35.5 + 10.1

b 654.2 + 0.34

c 54.678 − 5.3974

d 7 + 45

e 70 − 9.8

f 69.95 + 0.063

Question 4

Compute the following mathematical results following correct significant figure conventions.

a 3.4×8.23

b $9.45 \div 300$

c 539×23

d $(3.56 \times 10^6) \times 4.7$

e $10 \div 0.003$

f 0430×54.21

Question 5

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

a 3.2 kJ

b 8.0 pA

c 750 nm

d 500 ms

e 0.300 µg

f 54 MΩ

Question 6

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

A miles

B metres cubed (m^3)

C litres

D grams

E celcius

F pounds

G hours

H seconds

I light years

J volts

K electron volts

L ohms

EXAM-STYLE QUESTIONS

This lesson

Question 7 (5 MARKS)

In each of the following cases, provide your answers to the appropriate number of significant figures.

a Calculate the magnitude of the net force acting on a block. The mass of the block, *m*, is measured to be 250 g and the magnitude of its acceleration, *a*, is measured to be 3.0 m s^{-2}. The net force can be calculated using $F_{net} = ma$. (2 MARKS)

b Calculate the average speed for the journey of a cyclist who takes 22.0 seconds to ride a distance of 132 m along a road and a further 56 m along a footpath. Average speed is calculated using $speed = \frac{total\ distance}{time}$. (3 MARKS)

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 key knowledge dot point

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (gravity, magnetism, electricity, Newton's laws of motion, waves), and/or the construction and evaluation of a device; precision, accuracy, reliability and validity of data; and identification of, and distance between, uncertainty and error

Study design 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	4.3.3.2
Uncertainty	4.3.3.3
Precision and accuracy	4.3.3.4
Validity	4.3.3.5
Repeatability and reproducibility	4.3.3.6

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 design, 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 result from the actual results, often due to a problem with the experimental design or calibration of equipment

uncertainty a quantitative indicator of a range that the 'true' value of a measurement should lie within

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

Error 4.3.3.2

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 design, 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 contaminating samples, breaking equipment, and using the wrong formula in data analysis.

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 greatly 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.

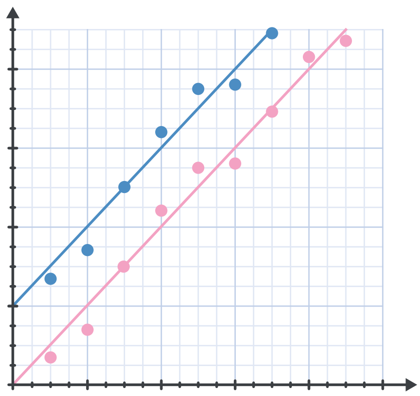


Figure 1 Plots of two experiments measuring a relationship between the same two variables. The 'true' relationship is linear and passes through the origin. The measurements plotted in blue have been affected by systematic error since all measurements are consistently above the 'true' values. All measurements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

Uncertainty 4.3.3.3

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.

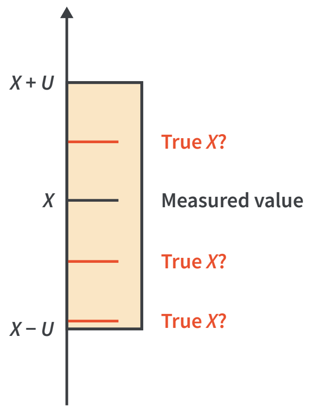


Figure 2 A quantity is measured to be $X \pm U$. This indicates the ‘true’ value of a measured quantity X should lie within the range of uncertainty U around X. It should not be assumed that the measured value X is the ‘true’ value.

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 ± 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 ruler 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 this ruler, the side of this box should be recorded as 5.40 ± 0.05 cm.

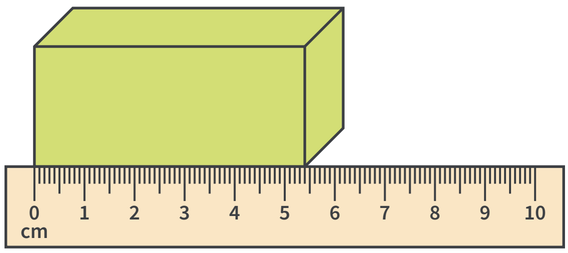


Figure 3 A box being measured by a ruler. The smallest increment on the ruler is 0.1 cm.

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).

1 **Worked example**

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

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

Difference between average and most extreme value: $|19.8 - 18.2| = 1.6 \text{ N} \approx 2$ N

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

Therefore, average net force is 20 ± 2 N

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.

2 **Worked example**

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

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

Difference between average and most extreme value: $|20.5 - 20.2| = 0.3$ N

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

Therefore, average net force is 20.2 ± 0.5 N

Precision and accuracy 4.3.3.4

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 a 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 **accuracy of a set of measurements** can be improved 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 a more accurate set of measurements, identify the data set with an average that is closer to the 'true' value.

Validity 4.3.3.5

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 4.3.3.6

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:
  1. Personal error – mistakes in an experiment’s design, execution or analysis
  2. Systematic error – a consistent, repeatable deviation in the measured result from the actual results
  3. 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
https://www.vcaa.vic.edu.au/curriculum/vce/vce-study-designs/Physics/advice-for-teachers/Pages/MeasurementinScienceOverview.aspx

1C Questions

THEORY REVIEW QUESTIONS

Question 1

Choose whether the following statements are true or false.

- **a** A value measured in an experiment can be known with complete certainty.
- **b** Uncertainty is always a “bad” thing.
- **c** Uncertainty is unavoidable.
- **d** Data that is known to have been affected by personal error should be kept and treated to be as valid as all other data.
- **e** Data should be manipulated until the uncertainty is as small as possible.
- **f** Systematic error is often caused by poor calibration of equipment.
- **g** Random error will always occur.
- **h** Random error can be reduced by using more precise equipment.
- **i** The uncertainty in the average of multiple measurements is the magnitude of the difference between the most extreme value and the average value.
- **j** A single set of measurements can be accurate and precise.
- **k** Observer bias makes an experiment invalid.
- **l** Validity in an experiment is determined only by the experimental design.
- **m** An experiment being reproducible increases the reliability of its conclusions.

EXAM-STYLE QUESTIONS

This lesson

Question 2 (1 MARK)

The best description of experimental uncertainty in a measurement is

- **A** how confident a scientist feels while performing data analysis.
- **B** a quantitative estimate of the random error associated with the measurement.
- **C** the difference between a measured value and its ‘true’ value.
- **D** the process of repeating a measurement to improve reliability.

Adapted from 2018 VCAA Exam Section A Q18

Question 3 (1 MARK)

Which of the following is a true statement about uncertainty?

- **A** Repeated measurements can eliminate uncertainty.
- **B** Personal error should be included when calculating uncertainty.
- **C** The ‘true’ value lies exactly in the middle of the range indicated by the uncertainties.
- **D** Using more precise equipment can reduce the level of uncertainty.

Question 4 (1 MARK)

Which of the following statements about repeating readings is correct?

- **A** Repeating readings reduces the effect of systematic error.
- **B** Repeating readings reduces the effect of random error.
- **C** Repeating readings increases the effect of systematic error.
- **D** Repeating readings has no effect on random error.

Adapted from 2018 VCAA NHT Exam Section A Q20

Question 5 (1 MARK)

Which of the following statements about systematic and random errors is incorrect?

- **A** Systematic errors affect all data points equally.
- **B** Systematic errors are unavoidable.
- **C** Random errors 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 always produce results that agree with the original experiment when performed by a different experimenter.
- **B** When the results of an experiment are published, they are deemed repeatable, reliable, and reproducible by the scientific community.
- **C** Reproducibility helps to discover bias and experimental flaws in the original experiment.
- **D** A reproducible experiment may not produce the same results if the second experimenter does not use the exact same equipment.

Question 7 (1 MARK)

Arshya and Thanushi measure the voltage across a resistor in the same circuit on separate occasions.

Arshya takes the following readings: 3.40 V, 4.20 V, 3.70 V, and 4.00 V (average 3.85 V).

Thanushi takes the following readings: 2.60 V, 3.80 V, 3.60 V, and 5.00 V (average 3.75 V).

The true value of the voltage is 3.70 V.

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

A Both sets of results are equally precise.

B Arshya's results are more accurate than Thanushi's results.

C Both sets of results are equally accurate.

D Thanushi's results are less precise than Arshya's results.

Adapted from 2017 VCAA Exam Section A Q18

Question 8 (1 MARK)

Some students set up the photoelectric effect to measure the value of Planck's constant which has a well established value of 6.63×10^{-34} J s. They take five measurements, as follows:

- 6.67×10^{-34} J s
- 6.59×10^{-34} J s
- 6.63×10^{-34} J s
- 6.54×10^{-34} J s
- 6.72×10^{-34} J s

A reasonable measurement uncertainty for the students to cite is

A 0.09×10^{-34} J s

B 0.05×10^{-34} J s

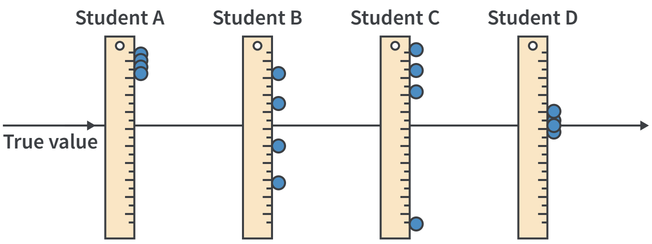
C 0.07×10^{-34} J s

D 0.005×10^{-34} J s

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 between two lenses. The measurements are then indicated as dots on a ruler (as shown on the diagram). The true value of the distance between the lenses is also indicated on the diagram.



Adapted from 2019 VCAA NHT Exam Section A Q19

Question 9 (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 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's results are the most precise and accurate?

A Student A

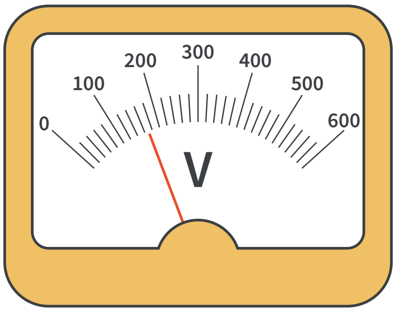
B Student B

C Student C

D Student D

Question 13 (1 MARK)

What is the best estimate for the uncertainty in this voltmeter?



A 20 V

B 10 V

C 5 V

D 1 V

Question 14 (2 MARKS)

What is experimental uncertainty? Identify one method by which experimental uncertainty can be reduced.

Adapted from 2019 VCAA NHT Exam Section B Q8a

Question 15 (2 MARKS)

Taking multiple measurements of the same quantity will not reduce the systematic error or random error in any individual measurement. Why, then, can taking multiple measurements improve the accuracy of experimental results?

Question 16 (8 MARKS)

Sam and Jess perform an experiment and measure the following frequencies of a wave. The true value of the frequency is known to be 64 Hz.

	Trial 1	Trial 2	Trial 3	Trial 4
Sam	68 Hz	76 Hz	54 Hz	66 Hz
Jess	79 Hz	81 Hz	60 Hz	64 Hz

a Calculate the average of Sam's results and the average of Jess' results. (2 MARKS)

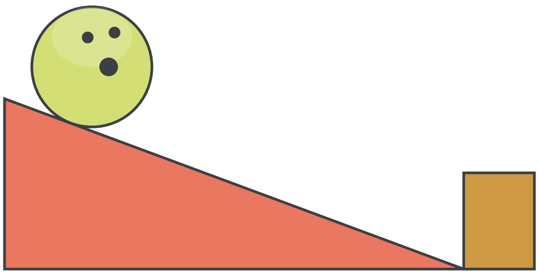
b Calculate the range of Sam's results and the range of Jess' results. (2 MARKS)

c Comment on the accuracy of Sam and Jess' results. (2 MARKS)

d Comment on the precision of Sam and Jess' results. (2 MARKS)

Question 17 (5 MARKS)

Claire designs an experiment to determine how the mass of a ball impacts the time it takes for the ball to go down a ramp. There is a stopper at the end of the ramp. 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.



a The mass of the ball is varied between 5 kg and 10 kg in 1 kg increments.

b Children's bowling balls are used as the 5 kg and 6 kg balls, small bowling balls are used for the 7 kg and 8 kg balls and large bowling balls are used as the 9 kg and 10 kg ball.

c A timer is used to measure the ball as it goes down the ramp. The timer is started when the ball is released and stopped when the ball hits the stopper.

d The length of the ramp, starting position of the ball, ramp material, and the angle of elevation of the ramp are kept constant throughout the experiment.

e Claire accidentally breaks the ramp by dropping one of the bowling balls on it and continues with the experiment.

f Claire stops the timer a bit after the ball hits the stopper so that the data better aligns with the trend she is seeing.

g Data is analysed to plot mass on the horizontal axis and time on the vertical axis.

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

i Claire concludes that having a shorter time for the ball to go down the ramp results in the mass of the ball being greater.

j Another student, Sally, is able to repeat Claire's experiment and get 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 key knowledge dot points

- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of uncertainty and error, 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 and scientific poster presentation, including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references

Study design 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	4.3.5.1 & 4.3.9.3
Drawing lines and curves of best fit	4.3.5.2 & 4.3.7.1

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 4.3.5.1 & 4.3.9.3

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 present 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.

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

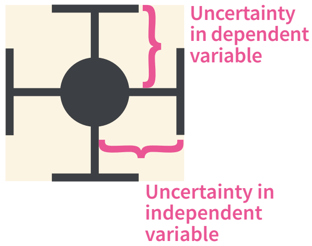


Figure 1 An example point with horizontal and vertical uncertainty bars. The yellow area indicates a range where the 'true' value might be located.

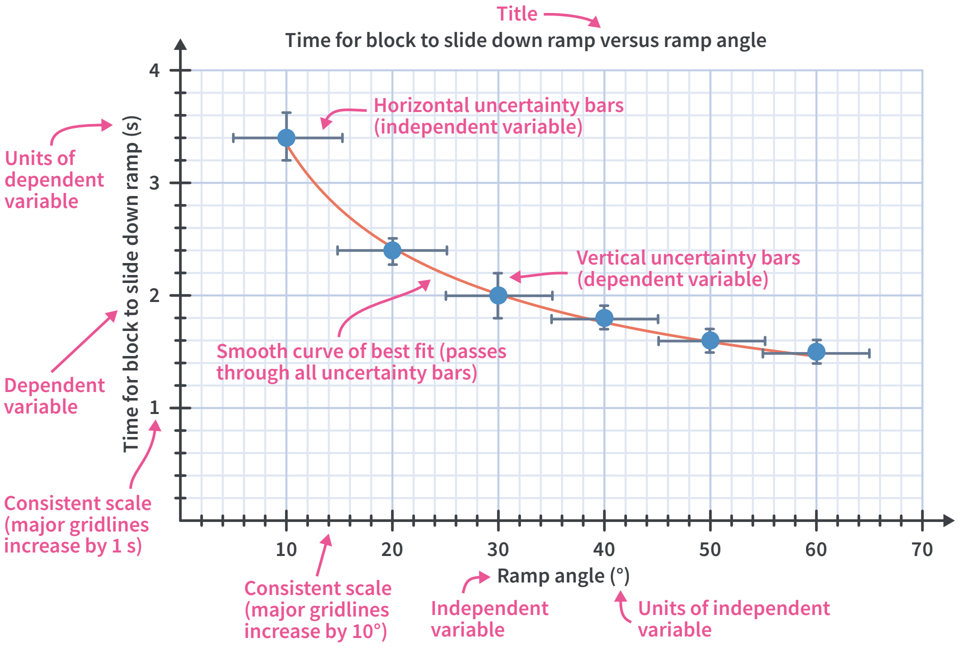


Figure 2 An annotated graph of the data from Table 1

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 $\left(\frac{1}{x}\right)$.

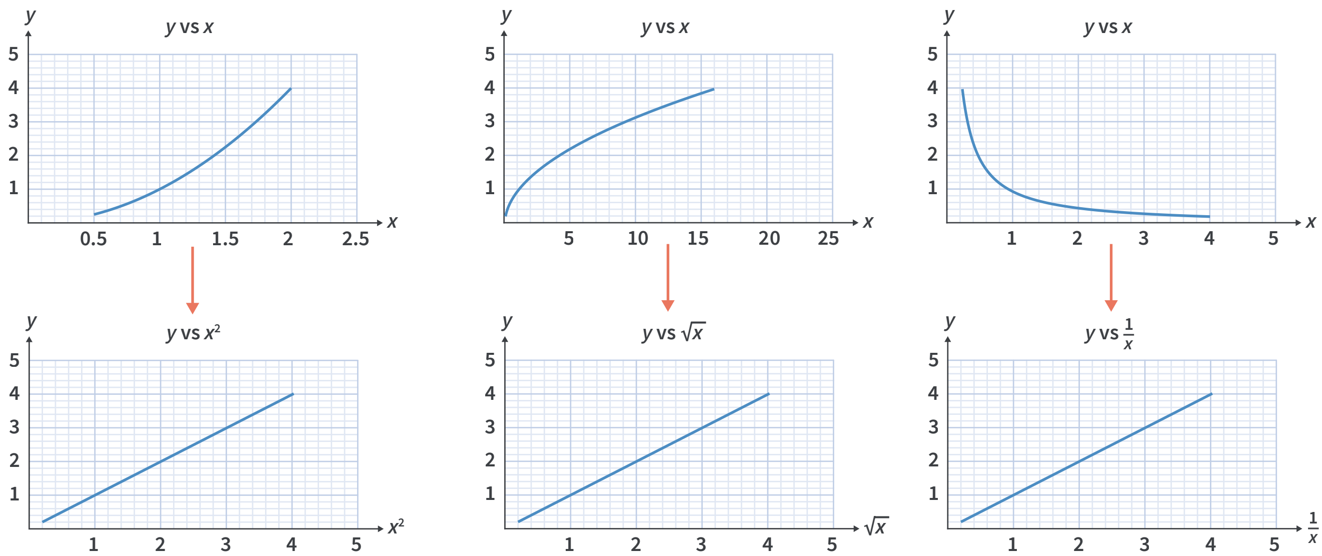


Figure 3 Examples of how different graphs can be linearised by transforming the independent variable. A straight line of best fit that passes through the origin means that the variables on the axes are proportional to each other.

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 $\sqrt{y} \propto x$.

1 Worked example

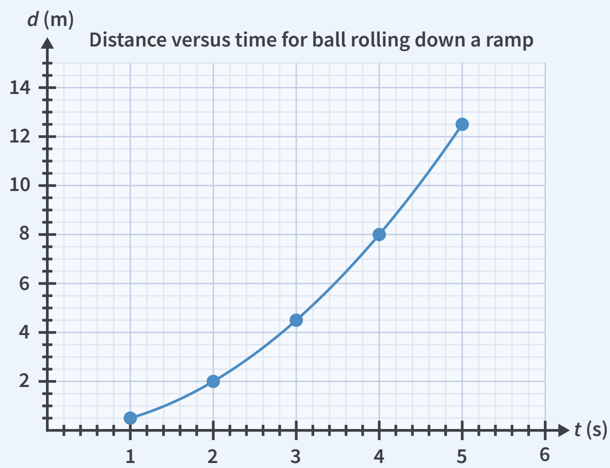
A student collected data on the distance travelled (d) by a ball that starts from rest and rolls down a ramp for different amounts of time (t). The angle of the ramp is fixed.

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

a Plotting this data results in the following graph:

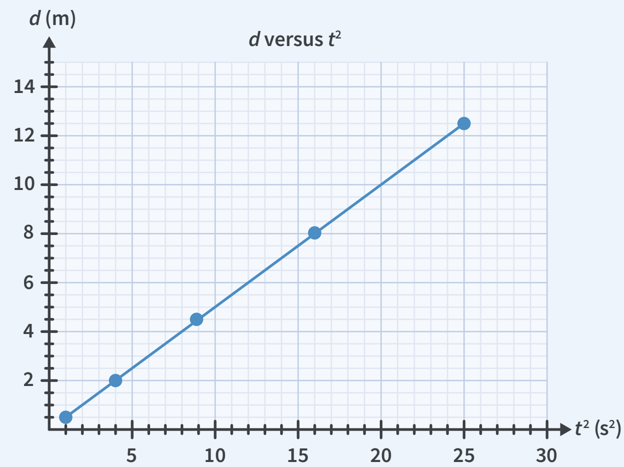


As the graph is curved, it is difficult to directly determine a relationship between d and t, so we linearise the data.

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

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

Now draw a graph with t^2 on the horizontal axis instead of t:



This data now fits a straight line of best fit. This indicates we have successfully linearised our data, which supports the relationship $d \propto t^2$.

Drawing lines and curves of best fit 4.3.5.2 & 4.3.7.1

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:

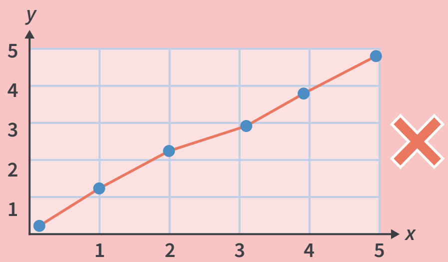
- Must pass through the uncertainty bars of all points (it does not need to pass through the specific data point)
- Should be smooth
- Should not be forced to pass through the origin
- Should not be forced to pass through the first and/or last point (or any point on the graph)
- Should not extend significantly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

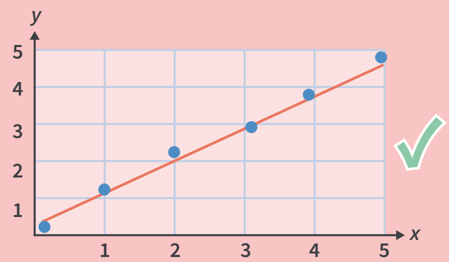
The reason for not forcing the line or curve of best fit through the origin, first point, or last point is that all data points are equally important. Forcing it through one of these points would incorrectly give that point more importance than the other data points when determining the overall trend.

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.

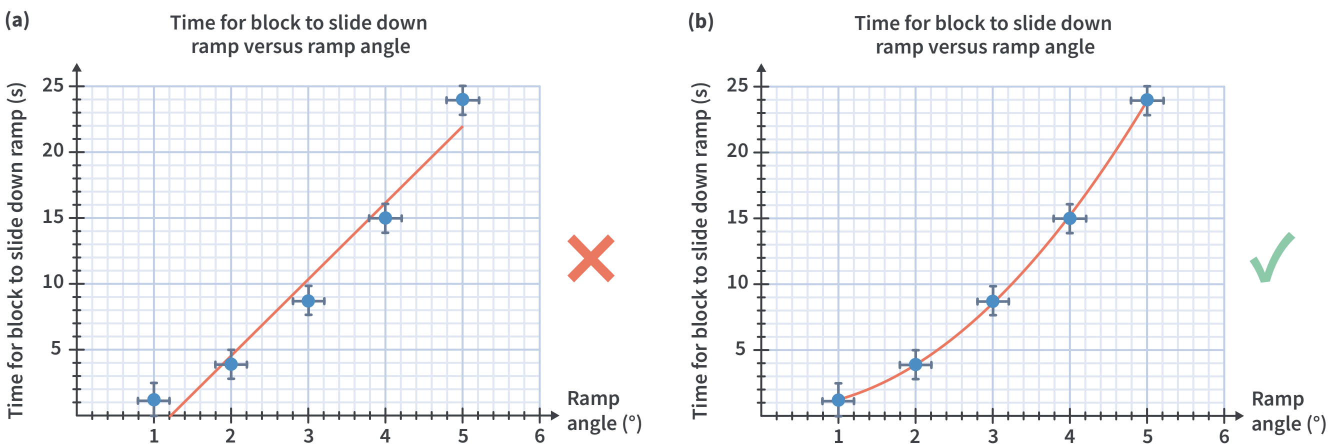


Figure 4 **(a)** The line of best fit is not valid as it does not pass through the uncertainty bars of all points.
(b) The curve of best fit is valid as it passes through the uncertainty bars of all points.

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:

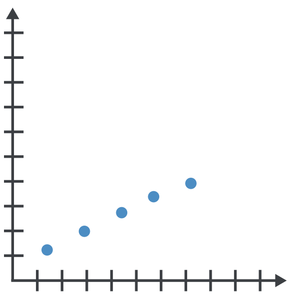
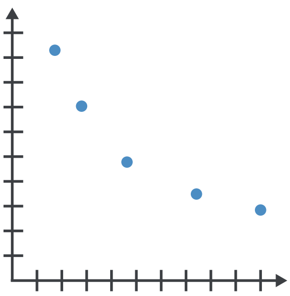
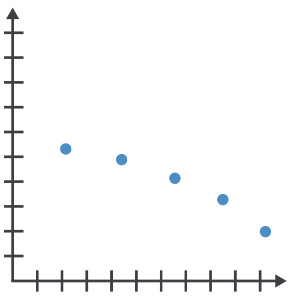
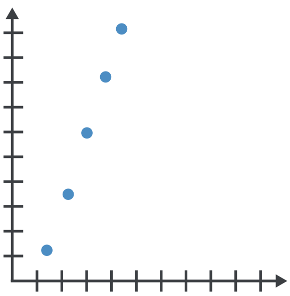
- Must pass through the uncertainty bars of all points (it does not need to pass through the specific data point)
- Should be smooth
- Should not be forced to pass through the origin
- Should not be forced to pass through the first and/or last point (or any point of the graph)
- Should not extend significantly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

1D Questions

THEORY REVIEW QUESTIONS

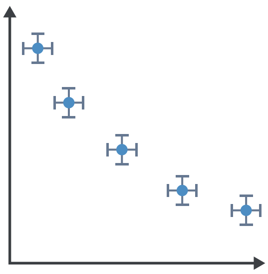
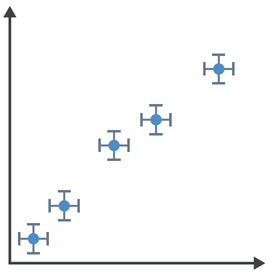
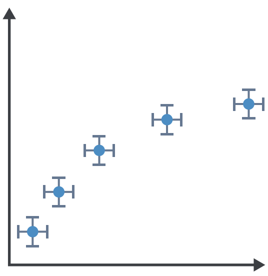
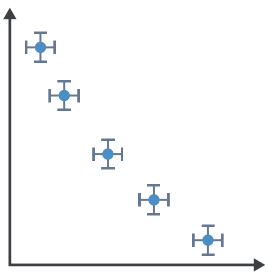
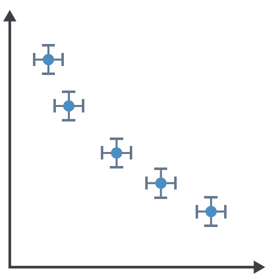
Question 1

The following graphs show different sets of data. Which graph has the most appropriately scaled axes for its set of data?

A

B

C

D


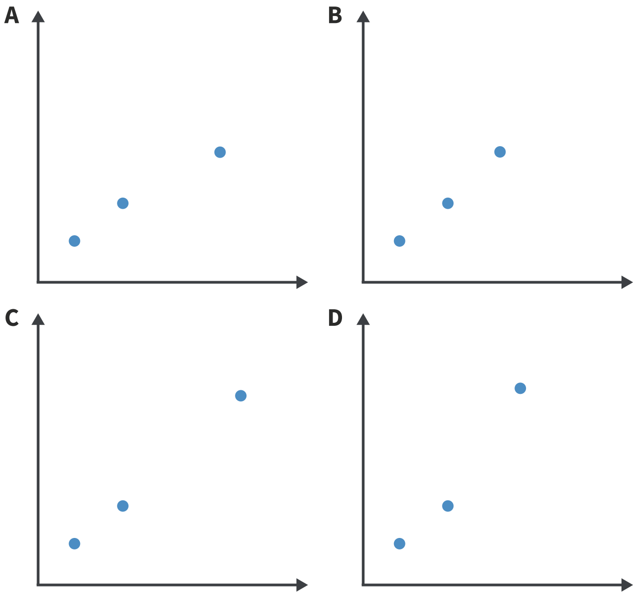
Question 2

For each of the following graphs, decide whether the data could be fitted with a line of best fit.

a

b

c

d

e


Question 3

A student creates a graph according to the graphing conventions with the data points (5, 3), (10, 6), and (20, 9). The scales on the axes have then been removed. Which of the following could be the student's graph?

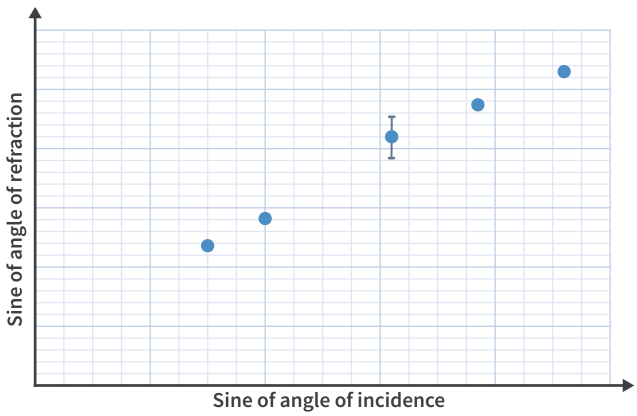


EXAM-STYLE QUESTIONS

This lesson

Question 4 (3 MARKS)

A student is part way through plotting a graph of the sine of an angle of refraction versus the sine of the angle of incidence for an experiment investigating index of refraction. The uncertainty in measuring the sine of the angle of incidence is negligible and the constant uncertainty in measuring the sine of the angle of refraction 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 (6 MARKS)

Jake and Sally record the data shown in the table below.

Distance between charges (10^{-12} m)	Uncertainty in distance between charges (10^{-12} m)	Force between charges (10^{-3} N)	Uncertainty in force between charges (10^{-3} N)
0.50	±0.05	0.92	±0.02
0.60	±0.05	0.64	±0.02
0.80	±0.05	0.36	±0.02
1.00	±0.05	0.24	±0.02
1.20	±0.05	0.16	±0.02

Using this data:

- Plot the force between charges versus distance between charges.
- Draw uncertainty bars for each data point.
- Draw a curve of best fit.

Include labels and scales for both axes.

Adapted from 2018 VCAA NHT Exam Section B Q10

Question 6 (6 MARKS)

Amelia places a single lightbulb into a circuit and varies the voltage of the power supply. She then measures the current passing through the bulb at each voltage.

She collects the following data:

Voltage, V (±0.5 V)	Current, I (±0.1 A)
1.0	1.5
2.0	2.5
3.0	3.3
4.0	3.8
5.0	4.0

a Draw a graph of this data with uncertainty bars and a line or curve of best fit as appropriate. (5 MARKS)

b An ohmic resistor will have a line of best fit on a graph of its current versus voltage. Is this light bulb an ohmic resistor? (1 MARK)

Question 7 (12 MARKS)

Michael studies the radius of the circular path, r, taken by an electron when it travels through a magnetic field with magnetic field strength B. Michael believes that $r \propto \frac{1}{B}$.

Magnetic field strength, B (T)	Uncertainty in magnetic field strength, B (T)	Radius, r (10^{-2} m)	Uncertainty in radius, r (10^{-2} m)
0.010	±0.005	2.3	±0.1
0.020	±0.005	1.1	±0.1
0.030	±0.005	0.8	±0.1
0.040	±0.005	0.6	±0.1
0.050	±0.005	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 $\frac{1}{B}$ and hence plot the graph of r versus $\frac{1}{B}$. 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 Michael's hypothesis that $r \propto \frac{1}{B}$ supported by his experimental data? (1 MARK)

Question 8 (13 MARKS)

Claire is investigating the relationship between the power rating (P) of various light bulbs and the current (I) that is measured to flow through the light bulbs when switched on in a simple circuit with a constant 230 V power supply. Her hypothesis is that $P \propto I^2$. She records the following data:

Power rating, P (± 0.5 W)	Measured current, I (± 5 mA)
4.0	18
8.0	35
9.5	42
14.5	63
20.0	87

a Plot a graph of current versus power based on the data above 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 I^2 and hence plot a graph that could support Claire's hypothesis. Only plot horizontal uncertainty bars, and include a line or curve of best fit as appropriate. (6 MARKS)

c Is Claire's hypothesis that $P \propto I^2$ supported by the data? Explain your answer with reference to the graphs created in part **a** and 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 key knowledge dot point

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

Study design 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	4.3.5.3
The meaning of a gradient	4.3.5.4

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	$gradient = \frac{y_2 - y_1}{x_2 - x_1}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

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 4.3.5.3

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 × 9.8 = 49 m s^{-1}.

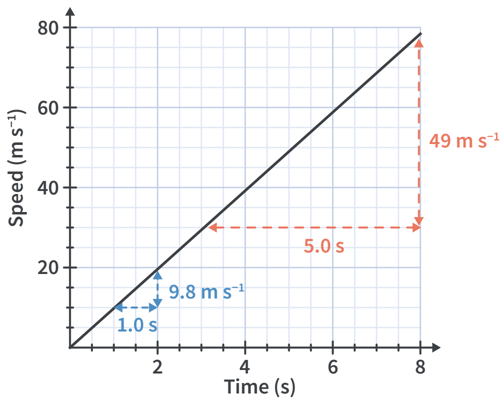


Figure 1 Speed vs time graph for an object in free fall without air resistance

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 $\frac{\textit{units on vertical axis}}{\textit{units on horizontal axis}}$.

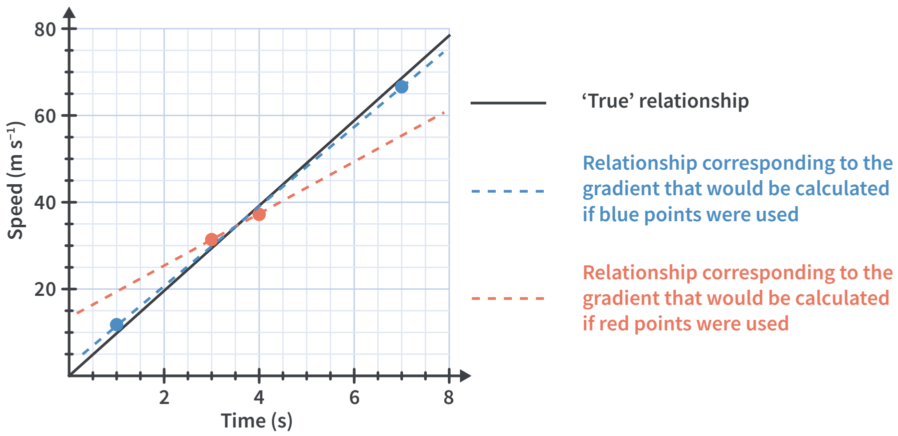
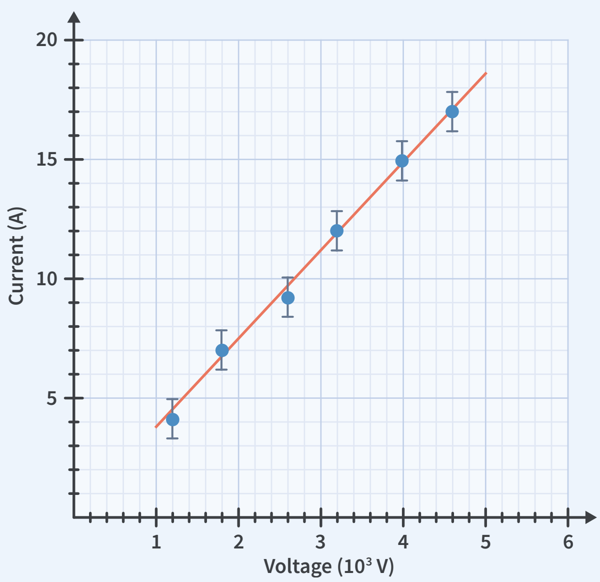


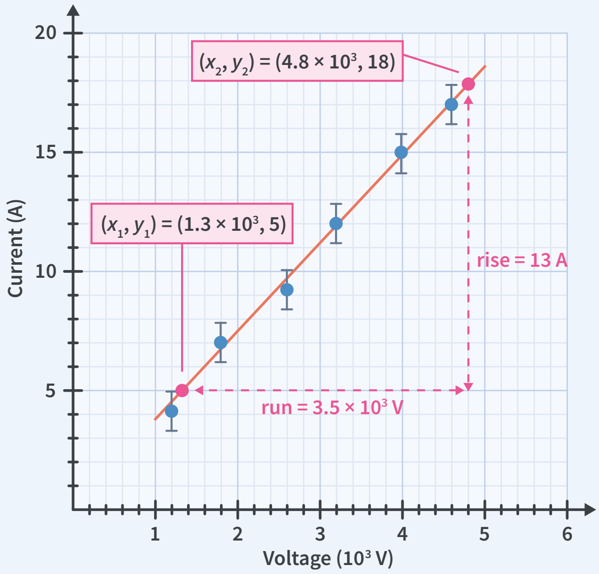
Figure 2 A small error when reading points from a graph can lead to a large error in the calculation of the gradient if the two points are close together.

1 Worked example

Find the gradient of this current versus voltage graph.



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 in the calculation of the run.

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

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

The meaning of a gradient 4.3.5.4

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 $\left(\textit{gradient} = \frac{\Delta y}{\Delta x}\right)$. 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 $\left(\textit{gradient} = \frac{y}{x}\right)$. 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, $\textit{gradient} = \frac{\textit{change in speed}}{\textit{change in time}} = \frac{\Delta v}{\Delta t}$. 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.

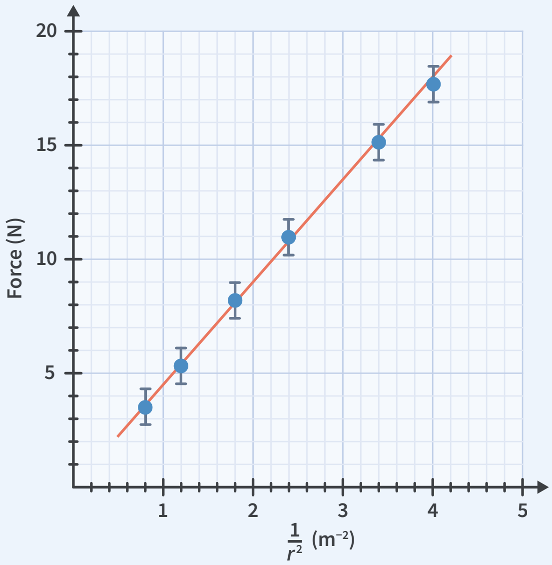
USEFUL TIP

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.

2 Worked example

The electric force that acts between two charges can be calculated from the equation $F = \frac{kq_1q_2}{r^2}$, where $k = 8.99 \times 10^9$ N m^2 C^{-2} is a constant, q_1 and q_2 are the magnitudes of the charges, and r is the distance between the charges.

Scientists undertake an experiment where they measure the electric force that acts between two charges as the distance between the charges varies. They plot the data for F vs $\frac{1}{r^2}$ and draw a line of best fit as shown. The line of best fit has a gradient of 4.5 N m^2.



It is known that one of the charges has a value $q_1 = 2.0 \times 10^{-5}$ C. Use the gradient to calculate the value of the other charge, q_2.

The gradient represents $\frac{\Delta F}{\Delta\left(\frac{1}{r^2}\right)}$.

From the relationship $F = \frac{kq_1q_2}{r^2} = \frac{1}{r^2} \times kq_1q_2$, we can see that $F \to 0$ when $\frac{1}{r^2} \to 0$, so the line should pass through the origin.

Hence, *gradient* $= \frac{F}{\frac{1}{r^2}} = kq_1q_2$

$4.5 = 8.99 \times 10^9 \times 2.0 \times 10^{-5} \times q_2$

$q_2 = 2.5 \times 10^{-5}$ C

Note that, 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 and, hence, a range of possible values for q_2.

Theory summary

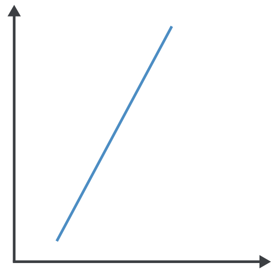
- Gradients can be calculated by finding two points **on the line of best fit** and substituting them into the formula: *gradient* $= \frac{y_2 - y_1}{x_2 - x_1}$.
  - Points should be chosen that are far apart on the line.
- By dividing the variables of the vertical axis by those of the horizontal axis,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

1E Questions

THEORY REVIEW QUESTIONS

Question 1

A gradient is calculated for the graph. This gradient is:



A positive and constant.

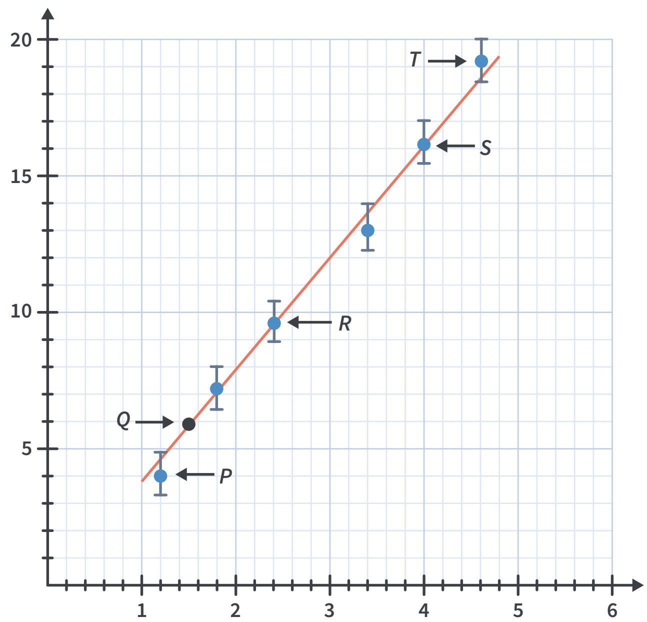
B negative and constant.

C positive and increasing.

D negative and decreasing.

Question 2

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?



Question 3

Data is collected for the force due to gravity (F_g) acting on objects with different masses (M_1, M_2). The data is plotted on a set of axes with F_g on the vertical axis and M_2 on the horizontal axis, and an appropriate line of best fit is drawn.

The equation that relates these quantities is $F_g = \frac{GM_1M_2}{r^2}$.

What would the gradient of the line of best fit represent?

A GM_1r^2

B $\frac{GM_1}{r^2}$

C $\frac{GM_2}{r^2}$

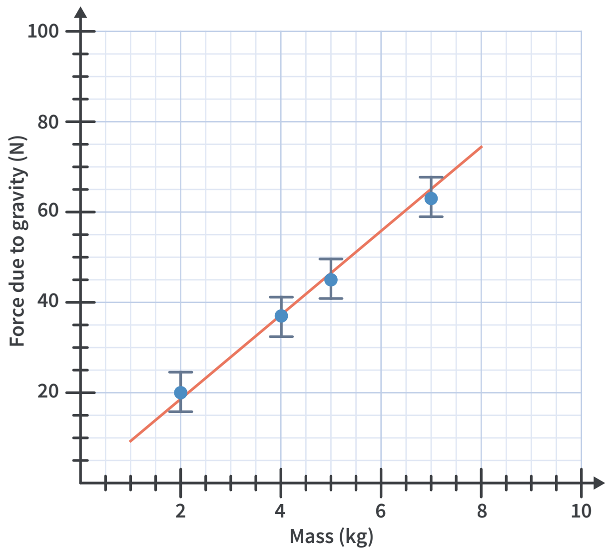
D GM_1r

EXAM-STYLE QUESTIONS

This lesson

Question 4 (2 MARKS)

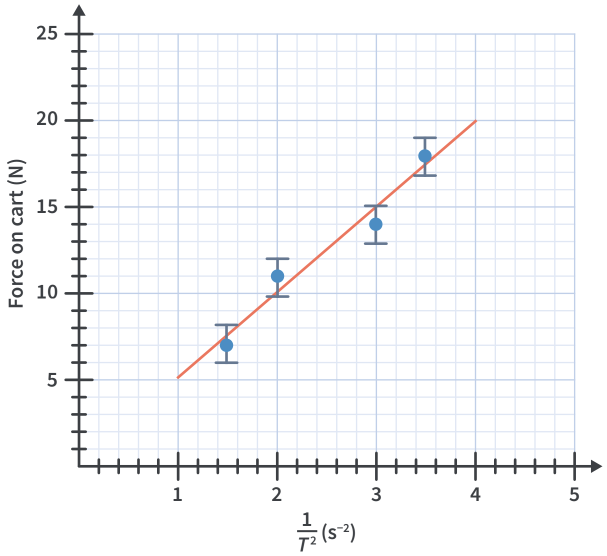
A student uses a set of scales to measure and record the force due to gravity for a range of masses and produces a line of best fit as shown. It is known that the force due to gravity is related to mass by the equation $F_g = mg$.



Use the gradient of the line of best fit to calculate the value of g determined in this experiment.

Question 5 (5 MARKS)

Data is collected for an experiment in which a cart travels with constant speed along a circular path. The net force acting on the cart, F, can be calculated from the equation $F = \frac{4\pi^2 mr}{T^2}$, where T is the time it takes to complete one revolution, m is the mass of the cart (kg), and r is the radius of the roundabout (m). The data is plotted on a set of axes with F on the vertical axis and $\frac{1}{T^2}$ on the horizontal axis. A line of best fit for the data is produced as is shown.

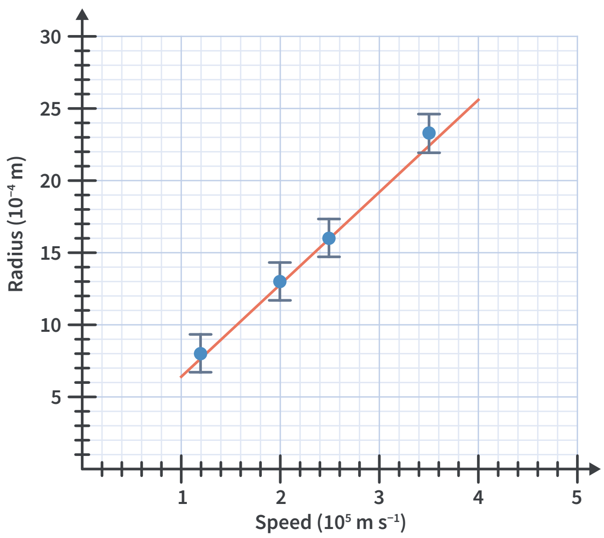


a Calculate the gradient of the line of best fit. (2 MARKS)

b If the radius of the circular path is 1.0 m, find the mass of the cart. (3 MARKS)

Question 6 (5 MARKS)

The radius of the circular motion of a charged particle which is moving perpendicularly through a magnetic field is given by the equation $r = \frac{mv}{qB}$, where m is the mass of the charged particle (kg), v is the speed of the particle (m s^{-1}), q is the charge of the particle (C), and B is the strength of the magnetic field (T). The graph shows a trendline for data which has been collected in an experiment involving an electron moving through a magnetic field (the data measurements are not shown).

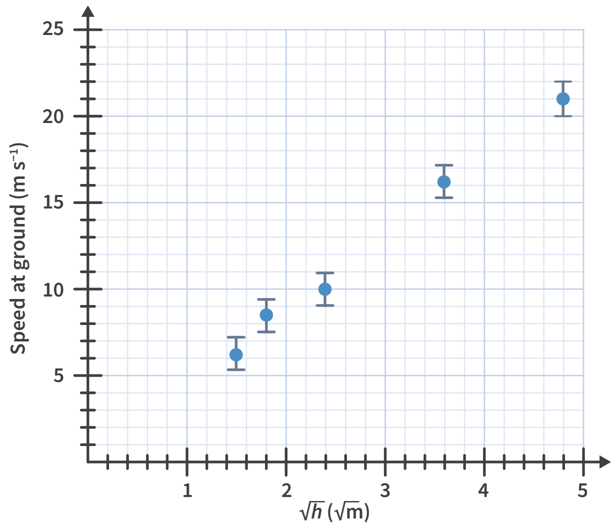


a Calculate the gradient of the line of best fit. (2 MARKS)

b Given that an electron has a charge of 1.6×10^{-19} C and the magnetic field used has a strength 8.7×10^{-4} T, use the gradient to find the mass of an electron. (3 MARKS)

Question 7 (6 MARKS)

CJ conducts an experiment to measure the speed of a cricket ball just before it hits the ground when released from rest at various heights. She finds the balls fall with the relationship $v = \sqrt{2gh}$ where v is speed (m s^{-1}), h is height (m), and g represents the magnitude of the acceleration due to gravity (m s^{-2}).



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 QUESTIONS

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 scientist measures the speed of light accurately to 3 significant figures. If the exact speed of light is 299 792 458 m s^{-1}, what was the measurement taken by the scientist?

A 2.9×10^8 m s^{-1} **B** 2.99×10^8 m s^{-1} **C** 3.0×10^8 m s^{-1} **D** 3.00×10^8 m s^{-1}

Question 2

Which of the following includes only SI units?

A Seconds, newtons, grams

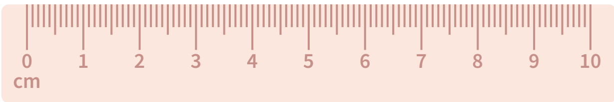
B Metres, seconds, kilograms

C Volts, kilojoules, watts

D Centimetres, joules, grams

Question 3

This ruler is used to measure the length of a metal block. Which of the following is the best measure of the uncertainty of this ruler?



A 0.1 cm **B** 0.5 cm **C** 1.0 cm **D** 0.05 cm

Question 4

Which of the following statements is correct?

A Repeating an experiment can reduce systematic error.

B Repeating an experiment can reduce random error.

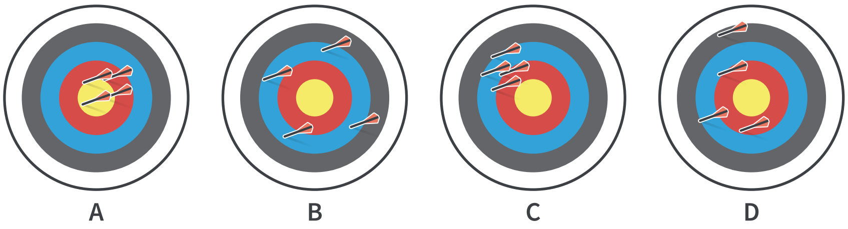
C Repeating an experiment can reduce both systematic and random error.

D Repeating an experiment cannot reduce systematic or random error.

Adapted from 2017 VCAA Exam Section A Q20

Use the following information to answer Questions 5 and 6.

Four students are trying archery for the first time and take four shots each, aiming at the centre of the target. The results of their attempts are shown on the targets.



Question 5

Which student produced results that were accurate but imprecise?

A Student A **B** Student B **C** Student C **D** Student D

Question 6

Which student produced results that were precise but inaccurate?

A Student A **B** Student B **C** Student C **D** Student D

Adapted from 2019 VCAA NHT Exam Section A Q20

Question 7

Which of the following best describes a hypothesis?

A An explanation that is widely accepted by the scientific community

B An explanation that is supported by a body of scientific evidence

C A possible explanation that will need to be supported by experimental evidence

D An explanation derived from a mathematical formula

Adapted from 2017 VCAA Exam Section A Q19

Question 8

A student measures the resistance of a resistor as 500 kΩ. What is the number of significant figures in this measurement?

A 1 **B** 2 **C** 3 **D** 6

Question 9

Which of the following best describes a scientific model?

A A description of a physical process that has been directly observed through experiment

B A representation of a physical process that cannot be directly experienced

C A method for how an experiment will be conducted

D A scaled down version of a larger object

Question 10

Gwen and Arthur are taking measurements of the velocity of a ball. Gwen obtains the following readings: 2.1 m s^{-1}, 2.5 m s^{-1}, 2.3 m s^{-1}, 2.4 m s^{-1}, 1.7 m s^{-1} (average 2.2 m s^{-1}). Arthur obtains the following readings: 2.2 m s^{-1}, 3.5 m s^{-1}, 1.2 m s^{-1}, 2.6 m s^{-1}, 2.5 m s^{-1} (average 2.4 m s^{-1}). The true value of the ball's velocity is 2.4 m s^{-1}. Which one of the following statements is most correct?

A Gwen's results are more accurate than Arthur's results.

B Both sets of results are equally accurate.

C Gwen's results are more precise than Arthur's results.

D Both sets of results are equally precise.

Adapted from 2017 VCAA Exam Section A Q18

Question 11

A student measures the thickness of a thin wire as 0.000540 m. The number of significant figures in this measurement is

A 2 **B** 3 **C** 6 **D** 7

Adapted from 2018 VCAA NHT Exam Section A Q18

Question 12

Which of the following best describes a scientific theory?

A A possible explanation of a physical observation that is currently lacking experimental evidence

B A hypothesis that describes the formation of physical phenomena that have not yet been proven

C An explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation

D A speculative guess as to the cause of a physical observation that is widely accepted by scientists

Question 13

Given that net force is equal to the product of mass and acceleration, the unit equivalent to newtons (N) is:

A kg m s^{-2}

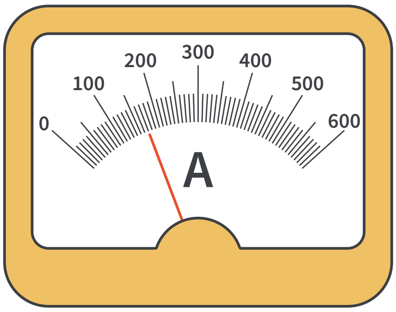
B kg m s^{-1}

C m A

D kg A

Question 14

The diagram shows a properly calibrated ammeter with its needle pointing close to a current of 170 A. Which of the following is the best measure of the uncertainty of this reading?



A 10 A

B 5 A

C 1 A

D 0.5 A

Adapted from 2018 VCAA Exam Section A Q19

Question 15

Anne is designing an experiment to calculate the impact of light intensity on current in the photoelectric effect. She changes the intensity of light as measured relative to a maximum value (20%, 40%, 60%, 80%) in each trial. She repeats the experiment three times at each intensity level and averages the current readings taken with the ammeter. She uses a red laser for the 20% and 40% light intensity and a green laser for the 60% and 80% light intensity. She ensures that the ammeter is zeroed and calibrated before the experiment.

This experiment is invalid. Which of the following is the best description of its invalidity?

A Changing light intensity and the colour of the light means that there is more than one independent variable in this experiment.

B Averaging the readings of each trial introduces the possibility of human error in the calculations.

C Calibrating the ammeter will be a source of systematic error in the experiment.

D Anne does not have the correct measuring device to measure the current in the circuit.

Question 16

Which of the following statements about reproducibility and repeatability is false?

A Repeatability refers to the ability of an experiment to be performed again a short while later by the **same** experimenter with the **same** equipment and produce the **same** results.

B Reproducibility refers to the ability of a **different** experimenter to perform the **same** experimental method again using the **same** equipment to produce **different** results.

C An experiment may not be repeatable or reproducible if it used small sample sizes or too few trials.

D Reproducing experiments is a method of checking for undisclosed systematic errors in the method of the first experiment.

Question 17

In the course of one experiment investigating voltage in a circuit, a student

- consistently reads an analogue voltmeter from an angle causing parallax error (error 1);
- finds that the voltage across a resistor varies in each trial with the same independent variable values (error 2); and
- incorrectly averages the three values by accidentally dividing by 4 instead of 3 (error 3).

Identify the kinds of errors.

	Error 1	Error 2	Error 3
A	Personal	Systematic	Random
B	Systematic	Random	Personal
C	Personal	Random	Systematic
D	Systematic	Systematic	Personal

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 18 (5 MARKS)

A student releases a ball with a mass of 1.0 kg from rest at the top of a fixed ramp of length 1.5 m. The student measures the speed of the ball at 1 second intervals. They repeat the experiment three times with the same ball and average the results of the speed at each time interval.

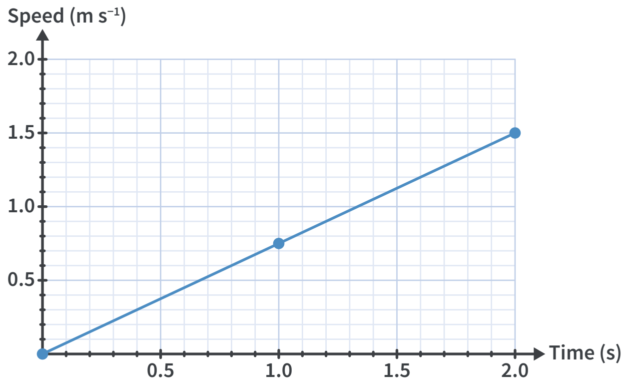
a Identify one example of each of the following kinds of variables:

i Independent variable (1 MARK)

ii Dependent variable (1 MARK)

iii Controlled variable (1 MARK)

b The student produces this graph of the results of their experiment.



Use this graph to calculate the magnitude of the acceleration of the ball given that acceleration can be found using the formula $a = \frac{\Delta v}{\Delta t}$. (2 MARKS)

Question 19 (12 MARKS)

A student is examining the power loss in a transmission line to understand the effect of changing the current on the resulting power loss. The uncertainty in the power loss is 50 W. She recorded the data in the table.

Power loss P (W)	Current I (A)
450	3.0
800	4.0
1250	5.0
1800	6.0

a Calculate the values of I^2 (in units of A^2) and add them as a column to a copy of this table. You should provide these values to a suitable number of significant figures. (2 MARKS)

b Identify whether current is an independent, dependent, or controlled variable. (1 MARK)

c Plot a graph of P versus I^2.

Remember to use an appropriate scale, include the correct uncertainty bars for P values, label each axis correctly, and draw a line of best fit. (6 MARKS)

d The relationship between power and current is $P = I^2 R$, where P is the power (W), I is the current (A) and R is the resistance (Ω). Using the line of best fit in part **c**, determine the value of the resistance of the transmission line in ohms. (3 MARKS)

Question 20 (16 MARKS)

An electrical engineer is testing Coulomb's law, which is an electromagnetic law that describes the force between two charged bodies.

The electrical engineer changes the separation between two charged spheres and measures the electrostatic force. The amounts of charge on the two spheres are kept constant.

a As a 'pilot study' of this experiment, the engineer measures the force between two charged metal spheres that are held 6.54 mm apart. Write this distance in SI units and scientific notation. (2 MARKS)

b Identify one example of an independent variable, dependent variable, and controlled variable in this experiment. (3 MARKS)

c The data recorded by the engineer is recorded in the table below. Calculate the values of $\frac{1}{r^2}$ in units of m^{-2} and add them as a column to a copy of this table. (2 MARKS)

Separation r (mm)	**Force (N)**
10.0	6.90×10^{-27}
20.0	1.73×10^{-27}
30.0	7.67×10^{-28}
40.0	4.31×10^{-28}

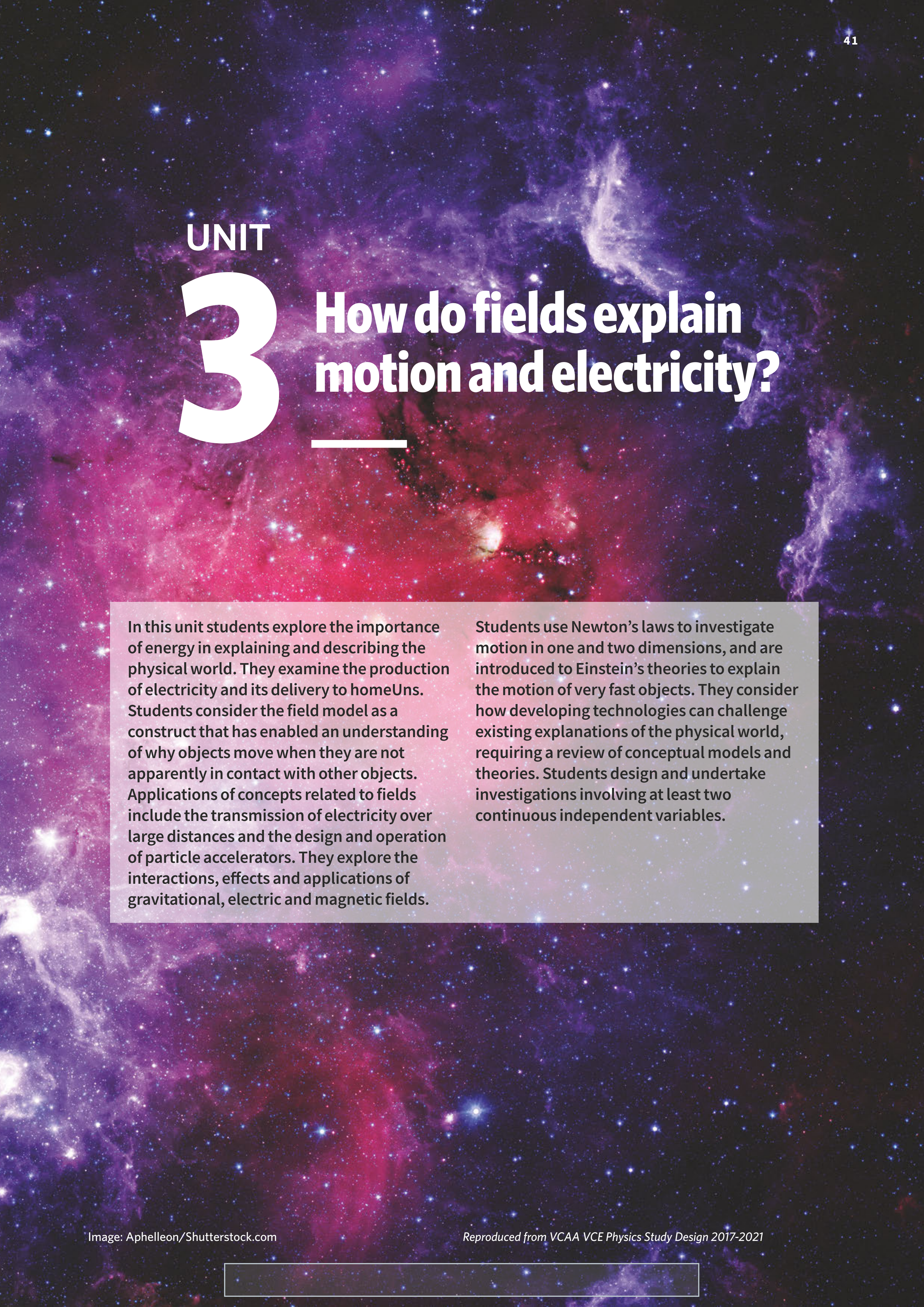
d Hence plot a graph of F versus $\frac{1}{r^2}$.

Remember to use an appropriate scale, label each axis correctly, and draw a line of best fit. (5 MARKS)

e The relationship described by Coulomb's law is given by $F = \frac{kq_1q_2}{r^2}$, where F is the force between the two bodies in newtons (N), q_1 is the charge of one body in coulombs (C), q_2 is the charge of the second body in coulombs (C), and r is the separation between the bodies in metres (m). k is a constant called Coulomb's constant.

The value of q_1 is 5.00×10^{-20} C and the value of q_2 is 1.50×10^{-21} C.

Use the line of best fit in part **d** to determine the value of Coulomb's constant, k, that would be obtained in this experiment. Give your answer in N m^2 C^{-2}. (4 MARKS)



UNIT 3 How do fields explain motion and electricity?

In this unit students explore the importance of energy in explaining and describing the physical world. They examine the production of electricity and its delivery to homeUns. Students consider the field model as a construct that has enabled an understanding of why objects move when they are not apparently in contact with other objects. Applications of concepts related to fields include the transmission of electricity over large distances and the design and operation of particle accelerators. They explore the interactions, effects and applications of gravitational, electric and magnetic fields. Students use Newton's laws to investigate motion in one and two dimensions, and are introduced to Einstein's theories to explain the motion of very fast objects. They consider how developing technologies can challenge existing explanations of the physical world, requiring a review of conceptual models and theories. Students design and undertake investigations involving at least two continuous independent variables.

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UNIT 3

AOS3

How fast can things go?

In this area of study students use Newton's laws of motion to analyse relative motion, circular motion and projectile motion. Newton's laws of motion give important insights into a range of motion both on Earth and beyond. At very high speeds, however, these laws are insufficient to model motion and Einstein's theory of special relativity provides a better model. Students compare Newton's and Einstein's explanations of motion and evaluate the circumstances in which they can be applied. They explore the relationships between force, energy and mass.

Outcome 3

On completion of this unit the student should be able to investigate motion and related energy transformations experimentally, analyse motion using Newton's laws of motion in one and two dimensions, and explain the motion of objects moving at very large speeds using Einstein's theory of special relativity.

UNIT 3 AOS 3, CHAPTER 2

Force and motion

02

Key knowledge

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions
- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: $\left(F_{net} = \frac{mv^2}{r}\right)$, including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string
- model natural and artificial satellite motion as uniform circular motion
- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only)
- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance

Image: Sky Antonio/Shutterstock.com

2A KINEMATICS RECAP

The content in this lesson is considered fundamental prior knowledge from Unit 2. It can be used as revision or to bridge understanding for students who have not studied Unit 2 Physics.

This lesson examines the basic quantities of motion (displacement, velocity, and acceleration), distinguishes between vector and scalar quantities, and introduces the constant acceleration equations which will be heavily used throughout Chapter 2.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Key knowledge units	
Quantities of motion	2.1.2.1
Constant acceleration equations	2.1.2.2

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $v = u + at$
	* $s = ut + \frac{1}{2}at^2$
	* $s = vt - \frac{1}{2}at^2$
	* $v^2 = u^2 + 2as$
	* $s = \frac{1}{2}(v + u)t$
	* $v = \frac{\Delta s}{\Delta t}$
	* $a = \frac{\Delta v}{\Delta t}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

acceleration the rate of change of velocity per unit time (vector quantity)

displacement the change in position of an object (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 magnitude (size) and direction

velocity the rate of change of displacement per unit time (vector quantity)

Quantities of motion 2.1.2.1

OVERVIEW

Distance and displacement provide information about the physical position of an object. Velocity and speed provide information about the rate at which the object's position changes. Acceleration measures the rate at which the object’s velocity changes.

THEORY DETAILS

Vectors and scalars

A scalar quantity only has magnitude. A vector quantity has both a magnitude and an associated direction.

The direction component of a vector can be expressed in a variety of ways, such as stating a direction in words (like 'left' or 'east') or applying sign conventions. The most common convention is to assign one direction as positive and the opposite as negative. The problems in this chapter will deal with one dimensional and two-dimensional motion. In these problems, it is generally best to define one direction in the *y*-axis (generally 'up') and one direction in the *x*-axis (generally 'right') as positive and define the opposite directions as negative.

Displacement and distance

Distance is the total length of a path travelled between two points. It is a scalar quantity.

Displacement, in comparison, is the shortest path between two points. It is the distance "as the crow flies". Displacement is a vector quantity, so it always has an associated direction.

The SI unit for distance and displacement is metres (m).

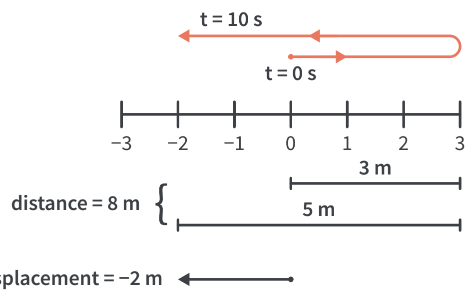


Figure 1 For an object travelling from 0 m to −2 m on the illustrated path, the distance covered is 8 m (5 m + 3 m) while the displacement is −2 m.

Velocity and speed

Velocity is the rate of change of displacement with respect to time. It is a vector quantity.

Speed is the rate of change of distance with respect to time. It is a scalar quantity. Both velocity and speed have the SI unit of metres per second (m s^{-1}).

In general, the velocity of an object for any given motion is not necessarily constant – it can speed up and slow down (and change direction) throughout the motion. Therefore we distinguish between average velocity (and speed) and instantaneous velocity (and speed). **Average velocity** describes the constant velocity that an object would have in order to travel between two points in a given time. The following formula is used to calculate the magnitude of the average velocity.

$$v = \frac{\Delta s}{\Delta t} = \frac{s_2 - s_1}{t_2 - t_1}$$

v = average velocity (m s^{-1}), s = displacement (m), t = time (s)

The **average speed** will be equal to the magnitude of the average velocity only if the direction of motion does not change.

Instantaneous velocity describes the velocity at an instant in time. The instantaneous velocity can be calculated using the formula for average velocity if the velocity is constant. Instantaneous speed is always equal to the magnitude of the instantaneous velocity.

USEFUL TIP

To convert from m s^{-1} to km h^{-1}, multiply by 3.6.

To convert from km h^{-1} to m s^{-1}, divide by 3.6.

1 **Worked example**

David runs one lap around a circular track with a circumference of 100 m in 25 seconds.

a **Calculate David's average speed.**

b **Calculate David's average velocity.**

a $d = 100$ m, $t = 25$ s

$s = \frac{d}{t} = \frac{100}{25} = 4.0 \text{ m s}^{-1}$

b $s = 0$ m (As one full lap is completed, David ends up back where he started)

$t = 25$ s

$v = \frac{\Delta s}{\Delta t} = \frac{0}{25} = 0 \text{ m s}^{-1}$

Acceleration

Acceleration is the rate of change of velocity per unit of time. The SI unit for acceleration is m s^{-2}.

We will only be considering cases of constant acceleration. Acceleration can be calculated using the following formula:

$$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{t_2 - t_1}$$

a = acceleration (m s^{-2}), v = final velocity (m s^{-1}), u = initial velocity (m s^{-1}), t = time (s)

It is important to note that because velocity is a vector quantity, if the direction of an object's motion changes then the velocity is changing (even if the speed stays constant). This means that an object changing direction is always accelerating.

If an object has an acceleration that is in the opposite direction to its motion, the velocity will reverse direction over time. The point at which the velocity is zero indicates the position where the object starts travelling in the opposite direction.

2 **Worked example**

Matt is riding on a tram that brakes over a duration of three seconds as it approaches a pedestrian crossing. The initial velocity of the tram is 11 m s^{-1} north and the final velocity is 2 m s^{-1} north. What is the acceleration of the tram over this time?

Take north as the positive direction: $u = 11 \text{ m s}^{-1}$, $v = 2 \text{ m s}^{-1}$, $\Delta t = 3$ s

$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$

$a = \frac{\Delta v}{\Delta t} = \frac{2 - 11}{3} = -3 \text{ m s}^{-2}$ north

The acceleration is negative because it acts in the opposite direction to the velocity (which is taken to be in the positive direction). Hence, the acceleration could also be decribed as 3 m s^{-2} south.

Constant acceleration equations 2.1.2.2

OVERVIEW

The constant acceleration equations are used to determine an unknown quantity of motion.

THEORY DETAILS

In analysing motion with constant acceleration, there are several equations which form a 'toolbox' that allow us to solve for either displacement (s), initial velocity (u), final velocity (v), acceleration (a), or time (t) if we know three of the other parameters.

These are commonly known as the 'SUVAT' equations because of these variables.

The derivation of these equations is not part of the VCE Physics course, but can be done using the equations already given in this chapter.

$$v = u + at$$
$$s = ut + \frac{1}{2}at^2$$
$$s = vt - \frac{1}{2}at^2$$
$$v^2 = u^2 + 2as$$
$$s = \frac{1}{2}(v + u)t$$

s = displacement (m), u = initial velocity (m s^{-1}), v = initial velocity (m s^{-1}), a = acceleration (m s^{-2}), t = time (s)

USEFUL TIP

When using the SUVAT equations which contain t^2 to solve for time, you may encounter a quadratic equation to solve. To avoid this, try using $v^2 = u^2 + 2as$ and $v = u + at$ to solve for time instead.

3 Worked example

a **Peter runs with an initial velocity of 2.00 m s^{-1} east and accelerates at −0.100 m s^{-2} east. Calculate how far Peter runs in 16.0 s.**

b **Jodie walks with an initial velocity of 1.70 m s^{-1} north and accelerates at 0.100 m s^{-2} south until reaching a velocity of 0.100 m s^{-1} north. Calculate how far Jodie walked.**

c **Christopher has an initial velocity of 2.00 m s^{-1} to the right but slows uniformly to a final velocity of 0.500 m s^{-1} to the right over a time of 10.0 s. Calculate Christopher's final displacement.**

a Take east as the positive direction: $u = 2.00$ m s^{-1}, $a = -0.100$ m s^{-2}, $t = 16.0$ s

$s = ut + \frac{1}{2}at^2 = 2.00 \times 16.0 + \frac{1}{2} \times (-0.100) \times 16.0^2 = 19.2$ m

Direction is not required for a distance.

b Take north as the positive direction: $u = 1.70$ m s^{-1}, $a = -0.100$ m s^{-2}, $v = 0.100$ m s^{-1}

$v^2 = u^2 + 2as \ \therefore 0.100^2 = 1.70^2 + 2 \times (-0.100) \times s$

$s = \frac{0.100^2 - 1.70^2}{2 \times (-0.100)} = 14.4$ m

Direction is not required for a distance.

c Take right as the positive direction: $u = 2.00$ m s^{-1}, $v = 0.500$ m s^{-1}, $t = 10.0$ s

$s = \frac{1}{2}(v + u)t = \frac{1}{2}(0.500 + 2.00) \times 10.0 = 12.5$ m to the right

Theory summary

- Displacement and distance provide information about the position of an object.
- Velocity and speed measure how an object moves.
- Acceleration measures the rate of change of an object's velocity.
- Displacement, velocity, acceleration and time are linked by the constant acceleration equations. These equations can be used to solve kinematic problems.

KEEN TO INVESTIGATE?

oPhysics 'Uniform Acceleration in One Dimension: Motion Graphs' simulation
https://www.ophysics.com/k4.html

oPhysics 'Uniform Acceleration in One Dimension' simulation
https://www.ophysics.com/k6.html

2A Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following is not a vector quantity?

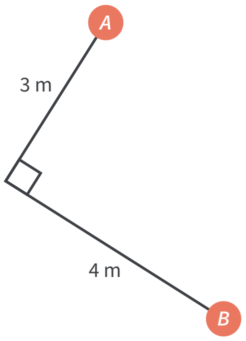
A Displacement

B Speed

C Velocity

D Acceleration

Use the following diagram to answer Questions 2 and 3.



Question 2

What is the distance covered travelling along the indicated path from point *A* to point *B*?

A 3 m

B 4 m

C 5 m

D 7 m

Question 3

What is the magnitude of the displacement travelling from point *A* to point *B*?

A 4 m

B 5 m

C 7 m

D 12 m

Question 4

What is the speed of a car travelling with an instantaneous velocity of -10 m s^{-1}?

A -10 m s^{-1}

B -5 m s^{-1}

C 5 m s^{-1}

D 10 m s^{-1}

Question 5

What is the speed of a car that travels a distance of 50 m in 10 seconds?

A 5.0 m s^{-1}

B 50 m s^{-1}

C 60 m s^{-1}

D 0.20 m s^{-1}

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

A swimmer swims one length of a 50 m pool with constant velocity. If they take 20 seconds, what is the magnitude of their velocity?

Question 7 (2 MARKS)

A car accelerates from 0 km h^{-1} to 36 km h^{-1} in 2.0 seconds. Calculate the magnitude of the acceleration of the car in m s^{-2}.

Question 8 (1 MARK)

A toy car accelerates at 0.30 m s^{-2} over 6.0 s. If the toy car has a final speed of 2.0 m s^{-1}, how far has the car travelled?

Question 9 (2 MARKS)

Calculate the final speed of the taxi driven by Donna if she observes the initial speed of the taxi to be 4.0 m s^{-1} and she accelerates at 0.50 m s^{-2} for 30 m.

Adapted from 2012 VCAA Exam Section A Q5c

Question 10 (2 MARKS)

Martha rides her bike down a hill, trying to go as fast as she can. She starts at an initial speed of 3.0 m s^{-1}, ends at a speed of 17 m s^{-1} and covers a distance of 30 m. How long does her descent take?

Question 11 (3 MARKS)

Calculate the initial speed in km h^{-1} of a truck that speeds up to 60 km h^{-1} over 3.6 seconds and a distance of 50 m.

Question 12 (2 MARKS)

Amy sleds down a hill. She starts at rest and accelerates at 3.0 m s^{-2}. It takes Amy 4.0 seconds to get to the bottom of the hill.

a Calculate the length of the path she travelled. (1 MARK)

b Calculate Amy's final speed at the bottom of the hill. (1 MARK)

Question 13 (5 MARKS)

Yasmin and Bill are trying to see who can slide further on a polished wood floor after taking a run-up. Yasmin's initial speed is 1.70 m s^{-1} while Bill's is 1.60 m s^{-1}. Yasmin decelerates (slows down) with a magnitude of 0.500 m s^{-2} whereas Bill decelerates at 0.400 m s^{-2}. Who travels further? Justify your answer with calculations.

Question 14 (3 MARKS)

Clara takes 10 seconds to run up a flight of stairs comprised of 15 steps. Each step is 30 cm tall. She slows down over the 10 seconds so that she is stationary when she gets to the top of the stairs. Calculate Clara's **average vertical** acceleration.

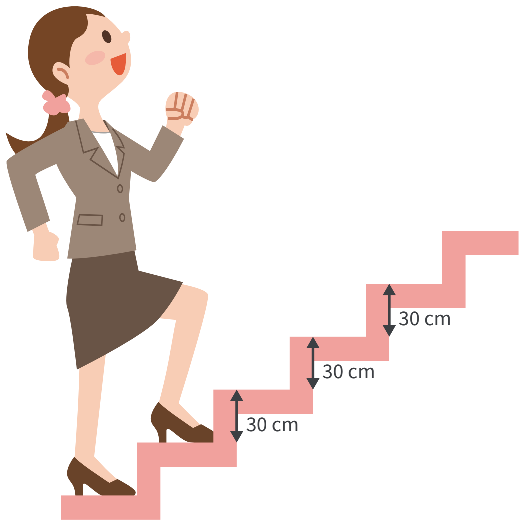


Image: ankomando/Shutterstock.com

Question 15 (4 MARKS)

Ryan starts jogging at 1.0 m s^{-1} and accelerates at a rate of 0.30 m s^{-2} over a distance of 10 m. Graham starts slower, jogging at 0.80 m s^{-1} and accelerates at a rate of 0.40 m s^{-2} over 5.0 seconds. Who ends up running at a faster pace? Justify your answer.

Question 16 (2 MARKS)

A shark accelerates at 2.0 m s^{-2} from its initial swimming speed of 1.5 m s^{-1}. It is hunting a stationary fish 10 m away. The fish intends to dart into a nearby cave (out of the shark's reach) 2.0 seconds after the shark starts accelerating. Can the shark catch the fish?

Question 17 (11 MARKS)

Rose's journey to the corner store is mostly flat but involves one hill at the end. This question will calculate the total time it takes for Rose to get to the store on her bike in sections.

a Calculate the time it takes Rose to travel the flat section totalling 600 m in distance if she rides at a constant speed of 2.5 m s^{-1}. (2 MARKS)

b Calculate the time it takes for Rose to ascend the 20 m path on the hill if she slows down at a rate of 0.10 m s^{-2}. (4 MARKS)

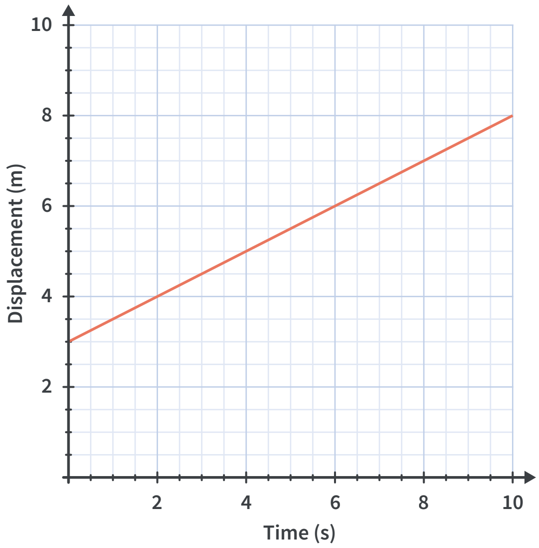
c Calculate the time it takes for Rose to descend down the hill if she speeds up at a rate of 0.60 m s^{-2}. The path down the hill is also 20 m long. (4 MARKS)

d Hence, calculate the total time it takes for Rose to ride to the store. (1 MARK)

Key science skills

Question 18 (6 MARKS)

Rory records his displacement versus time as he walks a distance of 5 m to the south and plots the following graph.



a Calculate the gradient of the trendline. (2 MARKS)

b Explain the physical interpretation of the gradient of the trendline. (2 MARKS)

c What is the magnitude and direction of Rory's velocity? (2 MARKS)

2B FORCES RECAP

The content in this lesson is considered fundamental prior knowledge from Unit 2. It can be used as revision or to bridge understanding for students who have not studied Unit 2 Physics.

This lesson revises knowledge of force vectors, including vector addition and subtraction in one and two dimensions. The lesson also revises the study of forces, including Newton's laws of motion, the net force, the gravitational force, and the normal force.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Key knowledge units	
1D force vectors	3.3.1.1.1
2D force vectors	3.3.1.1.2
Net force	3.3.1.3.2
Newton's first law	3.3.1.3.1
Newton's second law	3.3.1.3.3
Newton's third law	3.3.1.3.4
Gravitational force	3.3.1.4
Normal force	2.1.9.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $F_{net} = ma$
	$F_g = mg$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

equilibrium the state of having all the forces acting on an object in balance which means the net force on the object is zero

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

1D force vectors 3.3.1.1.1

OVERVIEW

Force is a vector quantity, and in one dimension the direction of a vector is either positive or negative.

Figure 1 Force vectors with magnitude *F* in the negative (left) and positive (right) directions. Here the positive direction has been defined as to the right.

THEORY DETAILS

Forces are vector quantities, having a magnitude and direction. The SI unit for force is the newton, N. In one dimension, the direction can either be positive or negative. The definition of which direction is positive should be explicitly stated. Positive direction is often defined as upwards or to the right.

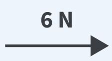
To add or subtract 1D force vectors simply add or subtract all forces, making sure to include signs to indicate direction.

1 **Worked example**

Add these two vectors.

Defining the positive direction to the right:

Vector sum = 14 + (−8) = 6 N



2D force vectors 3.3.1.1.2

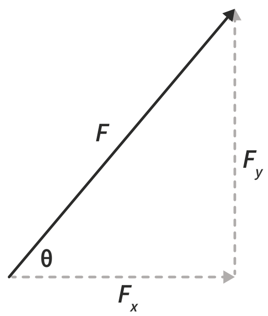
OVERVIEW

Forces in 2D can be resolved into their two 1D vector components to perform vector addition and subtraction.

THEORY DETAILS

The direction of a 2D force vector can be defined by the angle from an axis, or a direction such as 'North-West'. 2D forces can be broken down into two 1D force components in each of the force's dimensions. The 1D components forming a 2D force can be either positive or negative, depending on the definition of which directions are positive.

Trigonometry is used to determine the magnitude of a 2D force's components. Pythagoras' theorem and trigonometry is used to determine the magnitude and direction, respectively, of a 2D force vector from its 1D components.



$$F = \sqrt{F_x^{\,2} + F_y^{\,2}}$$

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

$$F_x = F\cos(\theta)$$

$$F_y = F\sin(\theta)$$

Figure 2 Equations relating the magnitude, *F*, and angle, θ, of a 2D force vector with its components in the *x*-*y* plane

USEFUL TIP

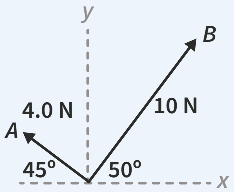
To add or subtract vectors (when drawn to scale) graphically and to get an idea of the direction of the resulting vector, add by joining vectors tip-to-tail. To subtract, flip the vector to be subtracted and join tip-to-tail.

To add or subtract 2D force vectors, break each 2D vector down into its 1D components and add or subtract the components in each direction to form two new 1D components. Then calculate the magnitude and angle of the 2D vector sum from its components.

2 Worked example

a Add force vectors A and B.

b Subtract vector A from vector B.



Defining the positive directions as to the right and upwards.

a Determine the x- and y-components:

$A_x = -4.0 \times \cos(45°) = -2.83$ N

$A_y = 4.0 \times \sin(45°) = 2.83$ N

$B_x = 10 \times \cos(50°) = 6.43$ N

$B_y = 10 \times \sin(50°) = 7.66$ N

Now add components:

$A_x + B_x = -2.83 + 6.43 = 3.60$ N

$A_y + B_y = 2.83 + 7.66 = 10.49$ N

Use components to determine new 2D force vector:

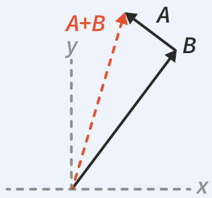
$A + B = \sqrt{3.60^2 + 10.49^2} = 11$ N

Define the angle of the vector from the positive x-axis:

$\theta = \tan^{-1}\left(\frac{10.49}{3.60}\right) = 71°$

Hence, $A + B = 11$ N at 71° from the positive x-axis.

Using the tip to tail method, this sum looks like:



b Using the previously computed x- and y-components:

$B_x - A_x = 6.43 - (-2.83) = 9.26$ N

$B_y - A_y = 7.66 - 2.83 = 4.83$ N

Use components to determine new 2D force vector:

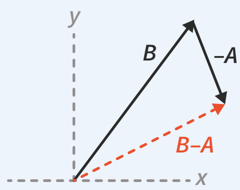
$A + B = \sqrt{9.26^2 + 4.83^2} = 10$ N

Define the angle of the vector from the positive x-axis:

$\theta = \tan^{-1}\left(\frac{4.83}{9.26}\right) = 28°$

Hence, $B - A = 10$ N at 28° from the positive x-axis.

Using the tip to tail method with the subtracted vector reversed, this difference looks like:



Net force 3.3.1.3.2

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 $F_{net} = \Sigma F$.

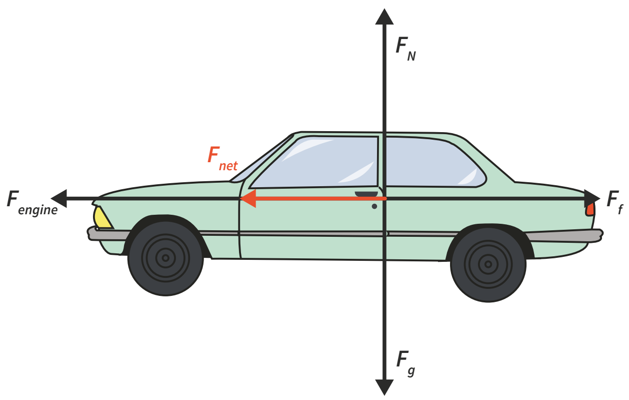
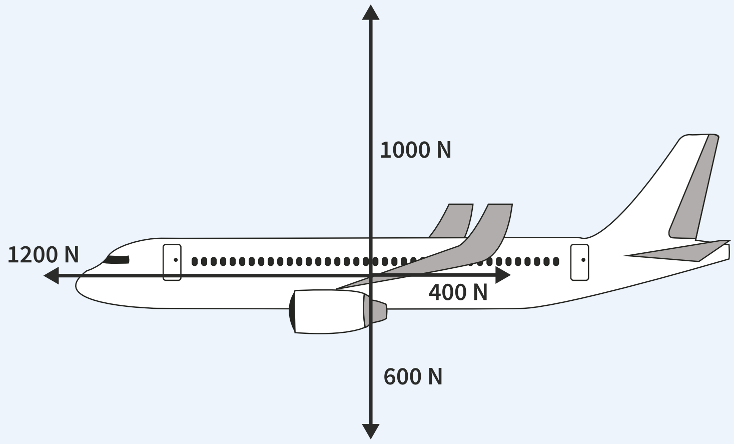


Figure 3 The net force on a car is the sum of all the forces acting upon the car.

3 Worked example

Determine the net force acting on the plane.



Define left and upwards as positive.

Calculate the sum of horizontal forces:

$F_{H\,net} = 1200 - 400 = 800$ N

Calculate the sum of vertical forces:

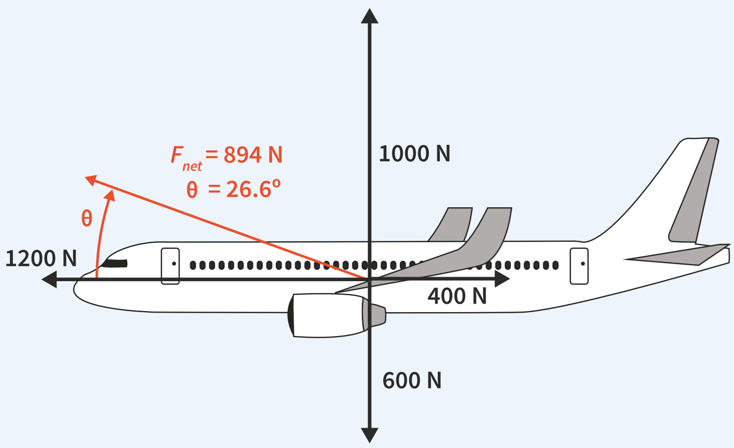
$F_{V\,net} = 1000 - 600 = 400$ N

$F_{net} = \sqrt{800^2 + 400^2} = 894$ N

Define the angle of the net force from the left horizontal axis.

$\theta = \tan^{-1}\left(\frac{400}{800}\right) = 26.6°$

Hence, $F_{net} = 894$ N at 26.6° from the left horizontal axis.



Newton's first law 3.3.1.3.1

OVERVIEW

Newton's first law is: **an object will accelerate only if a net force acts upon it**.

THEORY DETAILS

Newton's first law states that an object will accelerate only if there is a net force acting upon it. If there is no net force acting, the object will either remain at rest or keep moving at a constant velocity. This is known as being in equilibrium. An important conclusion of the law is that an object can be moving even if there is no force being applied.

For example, a rocket in the vacuum of space and away from the influence of gravity can move at a constant velocity without any force from its engine since there is no drag to slow it down. The net force is zero, so it will remain at a constant velocity.

Newton's second law 3.3.1.3.3

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 rearranged into the formula:

$$F_{net} = ma$$

F_{net} = net force (N), m = mass (kg), a = acceleration (m s^{-2})

Newton's third law 3.3.1.3.4

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.

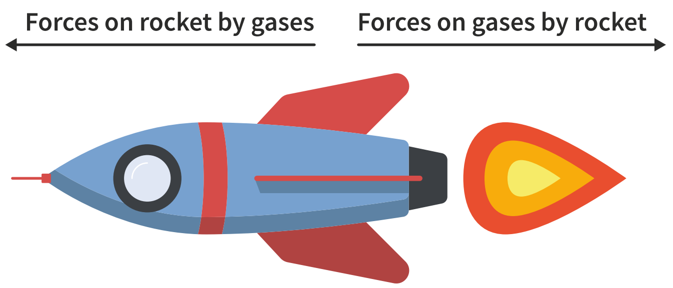


Figure 4 The action and reaction forces causing a rocket to accelerate in space

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 $\left(F_{\text{on } A \text{ by } B}\right)$ with the other force exerted on B by A $\left(F_{\text{on } B \text{ by } A}\right)$. Additionally, $F_{\text{on } A \text{ by } B} = -F_{\text{on } B \text{ by } A}$.

Gravitational force 3.3.1.4

OVERVIEW

The gravitational force 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 of gravity attracts masses towards each other. The acceleration of a mass due to gravity is equal to the gravitational field strength g at the mass' location. This quantity g is also known as the acceleration due to gravity, and it is independent of the mass being accelerated. At the Earth's surface, the acceleration due to gravity is 9.8 m s^{-2}. Applying Newton's second law, we find that the gravitational force on an object is given by:

$$F_g = mg$$

F_g = gravitational force (N), m = mass (kg), g = gravitational field strength/acceleration due to gravity (N kg^{-1} or m s^{-2})

The reaction force (remembering from Newton's third law that every action force has an equal and opposite 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 the force is negligible.

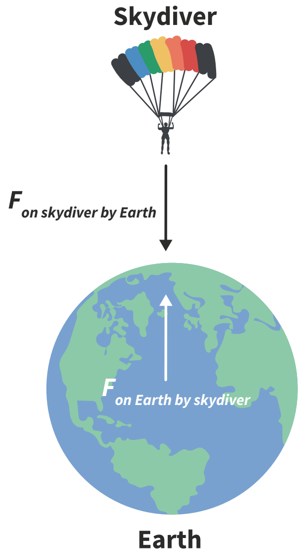


Figure 5 The gravitational action and reaction forces between a skydiver and the earth. The acceleration of the earth is negligible due to its large mass.

Normal force 2.1.9.1

OVERVIEW

The normal force is the equal and opposite reaction force that results from an object being in contact with and applying a force to another object.

THEORY DETAILS

When an object *A* is in contact with another object *B*, it exerts a contact force on that object, $F_{on\ B\ by\ A}$. Remembering Newton's third law, object *B* will exert an equal magnitude force on object *A* in the opposite direction, $F_{on\ A\ by\ B}$. This force is known as the normal force, F_N. For an object not accelerating, the normal force ensures that the net force on object *A* is zero, so it remains in equilibrium.

Note that the gravitational force on an object and the normal force on an object are **not an action/reaction pair**. Since gravitational force is **not** exerted on an object by the surface providing the normal force these forces are not an action/reaction pair. The action/reaction pair is the contact force and the normal force.

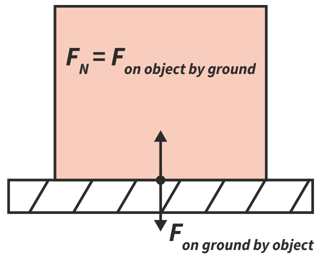


Figure 6 The normal force acting on an object *A* sitting on another object *B* as a result of the contact force on *B* by *A*

Theory summary

- Forces are vector quantities with SI unit newtons, N.
- 1D vectors can have a positive or negative direction.
  - Add or subtract 1D vectors using their direction signs.
- 2D vectors can be broken down into 1D components.
  - Use 1D components to add or subtract 2D vectors.
- Newton's laws:
  - 1st: An object will not accelerate unless a net force is applied.
  - 2nd: The acceleration of an object by a net force is equal to the net force divided by the mass of the object.
  - 3rd: Every action force has an equal and opposite reaction force.
- The gravitational force is $F_g = mg$.
- The normal force is the reaction force of an object in contact with another object.

KEEN TO INVESTIGATE?

oPhysics 'Vector Addition and Subtraction' simulation
https://ophysics.com/k2.html

oPhysics 'Vector Components' simulation
https://ophysics.com/k3.html

2B Questions

THEORY REVIEW QUESTIONS

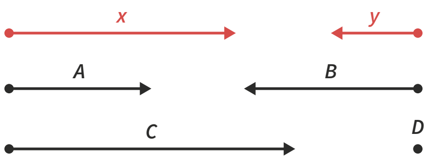
Question 1

Which option 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 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 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 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.

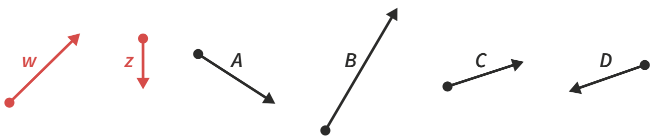
Question 2

Which single vector best represents the sum of the vectors x and y? Note that these vectors are drawn to scale.



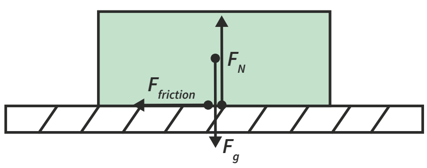
Question 3

Which single vector best represents the difference of the vectors w and z? Note that these vectors are drawn to scale.



Question 4

Which forces acting on this block contribute to the net force acting on the sliding block?



A None of these forces

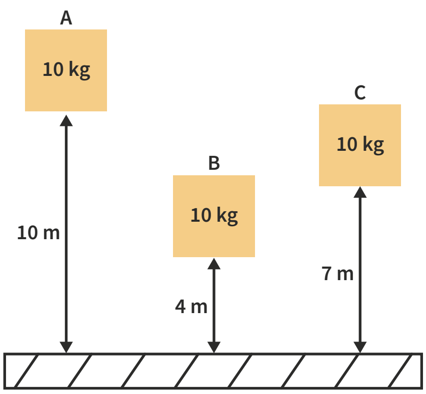
B Gravitational and normal force

C Gravitational and friction force

D All three forces

Question 5

Which of these three suspended masses in a uniform gravitational field has the largest gravitational force acting upon it?



A Mass A

B Mass B

C Mass C

D All masses have equal gravitational force acting upon them.

Question 6

The normal force is a

A reaction to a contact force.

B reaction to a gravitational force.

C gravitational force.

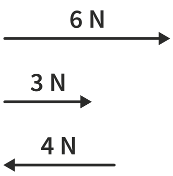
D nuclear force.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (2 MARKS)

Draw the vector sum of the three forces shown and label the magnitude of the resulting force.



Question 8 (1 MARK)

A force of 70 N acts on a 30 kg stone. Assuming there is no friction, determine the magnitude of the acceleration of the stone.

Question 9 (1 MARK)

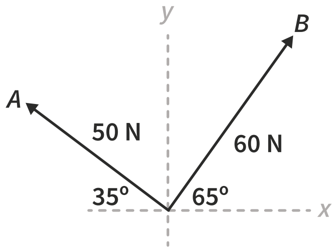
A 2000 kg race car accelerates at 30 m s^{-2} over a distance of 100 m. Determine the magnitude of the net force acting on the race car at this time.

Question 10 (2 MARKS)

Explain how the gases expelled by a rocket engine in one direction accelerate the rocket in the opposite direction, even when in the vacuum of space.

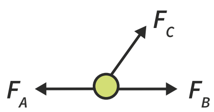
Question 11 (4 MARKS)

Determine the components of the two vectors A and B in the *x* and *y* direction.



Question 12 (2 MARKS)

Determine whether the three forces acting on this ball are able to hold it stationary. The forces can be made any non-zero magnitude, but cannot change direction. Justify your answer.



Question 13 (6 MARKS)

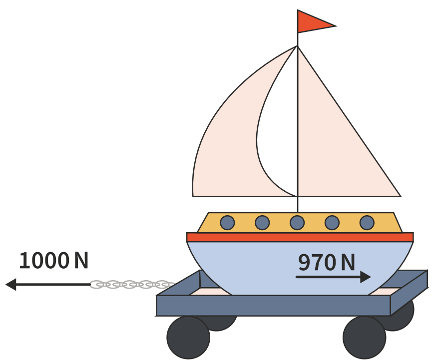
Four forces are acting on a 1000 kg boat being towed behind a car. The boat is not accelerating in the vertical direction.

a What is the gravitational force acting on the boat? Take upwards as positive. (1 MARK)

b What is the magnitude of the normal force acting on the boat? (1 MARK)

c Why is there a normal force present in this scenario? (2 MARKS)

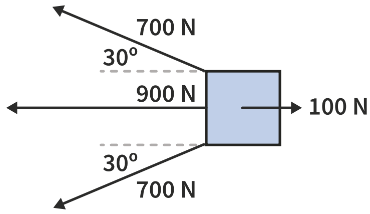
d The chain pulling the boat acts with a force of 1000 N, while air resistance acts on the boat with a force of 970 N. What is the magnitude of the net force acting on the boat? (1 MARK)



e Determine the magnitude of the boat's acceleration. (1 MARK)

Question 14 (4 MARKS)

Three friends are pulling a 70 kg esky full of kombucha against a friction force of 100 N.

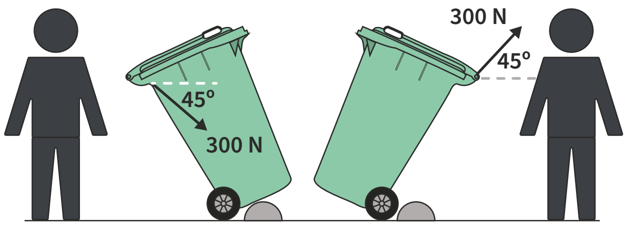


a Determine the magnitude and direction of the net force acting on the esky. (3 MARKS)

b Determine the magnitude of the esky's acceleration. (1 MARK)

Question 15 (6 MARKS)

Rami is struggling to push an 18 kg wheelie bin over a rock when his mother suggests he pull it over instead. Rami can push and pull with the same force of 300 N. When pushing, this force acts at 45° below horizontal. When pulling, the force acts at 45° above the horizontal.



a Taking upwards as the positive direction, calculate the vertical component of the force Rami is exerting in both cases. (2 MARKS)

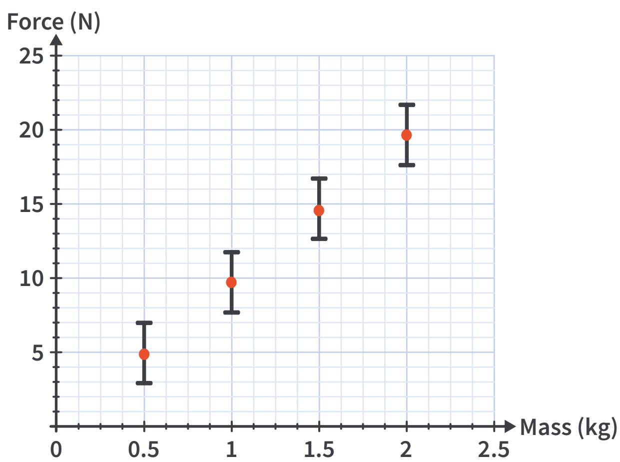
b Calculate the sum of the gravitational force and the vertical component of the force applied by Rami on the wheelie bin in each case. (3 MARKS)

c Evaluate whether Rami should push or pull the bin over the rock. (1 MARK)

Key science skills

Question 16 (4 MARKS)

Joanna conducts an experiment where she records the gravitational force acting on different masses and records her data in a graph.



a Plot a line of best fit on the graph. (2 MARKS)

b Determine a value for acceleration due to gravity, *g*, from the graph. (2 MARKS)

2C INCLINED PLANES AND CONNECTED BODIES

When towing a trailer up a hill, what are the relevant forces and in what directions do they act? This lesson develops the ideas of Newtonian mechanics and how they relate to the world around us. We will build on previous lessons to investigate how forces and kinematics are applied to inclined planes and connected bodies.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Study design key knowledge dot point

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions

Key knowledge units

Forces on inclined planes	3.3.1.5
Connected bodies in tension	3.3.1.6.1
Connected bodies in contact	3.3.1.6.2

Formulas for this lesson

Previous lessons		New formulas
2B	* $F_{net} = ma$	$F_{ds} = mg\sin(\theta)$
2B	$F_g = mg$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

connected bodies two or more objects either in direct contact or attached by a string, rope, or cable

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

Forces on inclined planes 3.3.1.5

OVERVIEW

For an object on an inclined plane, the normal force will act perpendicular to the plane, the gravitational force will act vertically downwards, and the net force will act down the plane.

THEORY DETAILS

We know that when an object rests on an inclined plane, such as a ball resting on a hill, it will accelerate down that surface if it is able to overcome friction. There are two forces which always act on an object on an inclined plane:

- The force due to gravity which acts vertically down
- The normal force which acts perpendicular to the inclined plane

In addition, there may be a friction force which acts parallel to the plane and opposite the direction of motion (if the object is sliding down the plane then the friction force acts up the plane).

These forces, when added together, result in a net force which acts parallel to the plane.

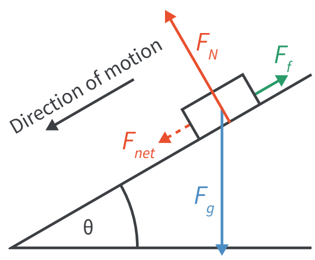


Figure 1 The forces that act on an object on an inclined plane. If there is a frictional force it will act opposite the direction of motion. In this case the frictional force is directed up the inclined plane because the motion is down the plane.

The force due to gravity can be resolved (separated) into two components: one perpendicular and one parallel to the inclined plane, as shown in Figure 2.

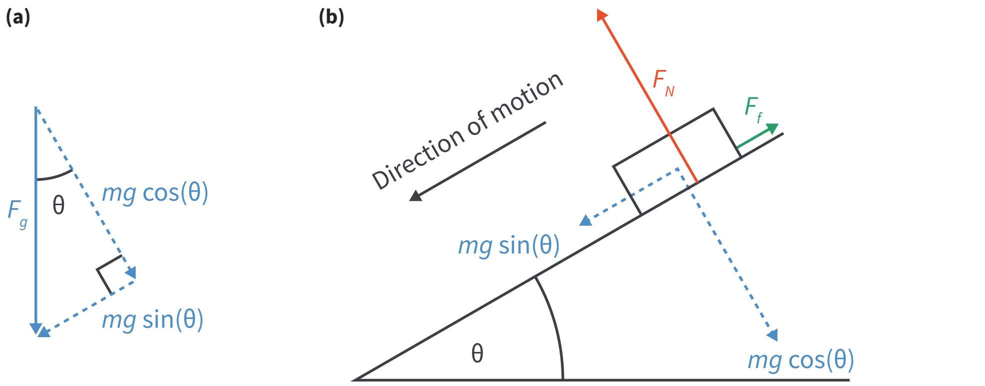


Figure 2 **(a)** The vector components of the force due to gravity which are parallel and perpendicular to an inclined plane. The angle between the force due to gravity and its component perpendicular to the plane is the same as the angle of the inclined plane to the horizontal (θ). **(b)** These components can replace the force due to gravity to simplify the analysis of motion on inclined planes.

$$F_{ds} = mg\sin(\theta)$$

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}), θ = angle of incline (°)

An object on an inclined plane does not accelerate perpendicular to the plane because the normal force has the opposite direction and equal magnitude to the component of the gravitational force which is perpendicular to the plane, $mg\cos(\theta)$. Therefore the net force on an object which is sliding down an incline has a magnitude given by $F_{net} = mg\sin(\theta) - F_f$.

USEFUL TIP

The net force and the components of the gravitational force are not forces in their own right. Therefore if we are asked to draw 'the forces acting on the object' on an inclined plane, we should not draw the net force or the components of the gravitational force – we should draw only the normal force, the force due to gravity (vertically down), and the friction force (if applicable). However, it is common for exam questions to ask us to draw the net force as well.

1 **Worked example**

A body of mass 2.0 kg is placed on a plane inclined at 35° to the horizontal. The inclined plane provides a constant frictional force of 4.0 N. Calculate:

a **The magnitude of the normal force acting on the 2.0 kg mass.**

b **The magnitude of the acceleration of the 2.0 kg mass down the slope.**

a The normal force will be equal to the component of the force due to gravity that is perpendicular to the inclined plane (see Figure 2)

$F_N = mg\cos(\theta) = 2.0 \times 9.8 \times \cos(35°)$

$F_N = 16$ N

b The net force down the slope on the mass will equal the force acting parallel down the inclined plane minus the frictional force

$F_{net} = F_{ds} - F_f = mg\sin(\theta) - F_f = 2.0 \times 9.8 \times \sin(35°) - 4.0$

$F_{net} = 7.24$ N

$F_{net} = ma \;\therefore 7.24 = 2.0 \times a$

$a = 3.6$ m s^{-2}

Connected bodies in tension 3.3.1.6.1

OVERVIEW

When two or more bodies are connected by a string or similar object that is being stretched or pulled, there is a tension force acting through the string in both directions. The two bodies will have the same acceleration. Newton's second law can be applied to whole connected body systems, or to individual bodies in order to find the acceleration and forces.

THEORY DETAILS

When two or more bodies are connected by a string and there is a force (or forces) which acts to separate the two bodies, there exists a tension force which acts in both directions pulling the bodies together. In VCE Physics, the string will be considered massless. Figure 3 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.

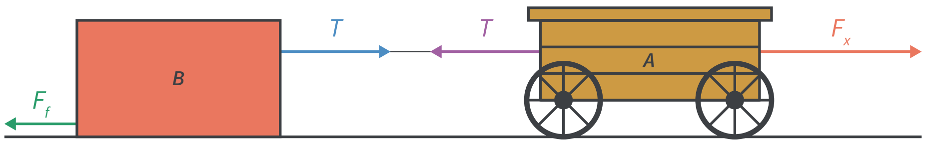


Figure 3 The horizontal forces involved for a cart, *A*, which is towing a block, *B*.

We can apply Newton's second law, $F_{net} = ma$, to any individual object or to the system of connected bodies as a whole. The acceleration will have the same value in all cases. It is important that we correctly consider the relevant forces and masses in each case.

When analysing the whole system, treat it 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.

When analysing a single object within the connected system:

- Consider only the forces acting directly on that object, including the tension force.
- Use only the mass of that object.

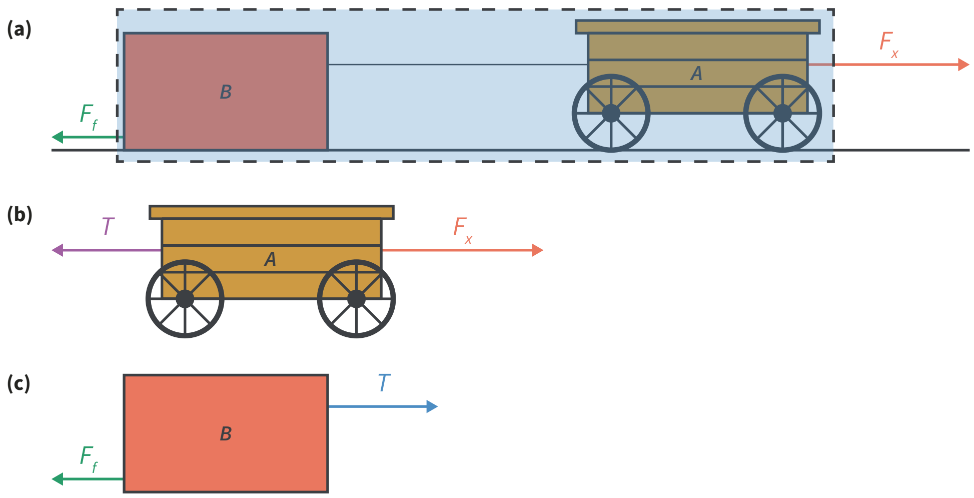


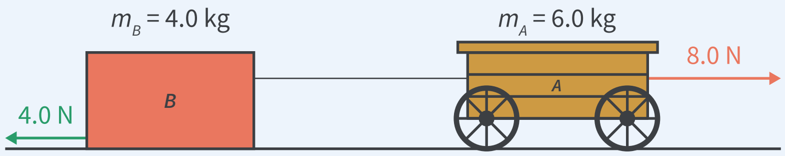
Figure 4 The relevant forces from Figure 3 when we analyse **(a)** the whole system, **(b)** only cart *A*, and **(c)** only block *B*.

If we take right as the positive direction in Figure 4, we can see that the relevant equations for considering

- the whole system are $F_{net} = F_x - F_f$ and $F_{net} = (m_A + m_B) \times a$.
- only cart A are $F_{net} = F_x - T$ and $F_{net} = m_A \times a$.
- only block B are $F_{net} = T - F_f$ and $F_{net} = m_B \times a$.

2 Worked example

A cart of mass 6.0 kg tows a block of mass 4.0 kg. The cart is pulled by a force of 8.0 N and there is a frictional force of 4.0 N acting on the block.



a **Calculate the magnitude of the acceleration of the cart.**

b **Calculate the magnitude of the tension force.**

a The cart and the block have the same acceleration. We do not yet know the tension force which acts on both the cart and the block. We will analyse the whole system (cart and block together) since this does not involve tension.

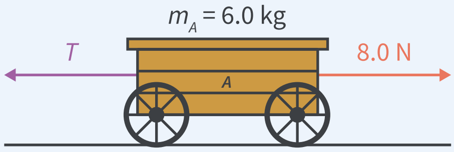
Consider the forces acting on the whole system: $F_{net} = F_x - F_f = 8.0 - 4.0 = 4.0$ N

Apply Newton's second law to the whole system: $F_{net} = (m_A + m_B) \times a \therefore 4.0 = (6.0 + 4.0) \times a$

$a = 0.40$ m s^{-2}

b Now we can analyse **either** the cart **or** the block individually to find the tension force.

We will use the cart.



Apply Newton's second law to the cart: $F_{net} = m_A \times a = 6.0 \times 0.40 = 2.4$ N

Consider the forces acting on the cart only: $F_{net} = F_x - T \therefore 2.4 = 8.0 - T$

$T = 5.6$ N

We can make similar calculations when one of the connected masses is hanging over an edge via a pulley as shown in Figure 5(a). The only difference is that the force due to gravity acting on the hanging mass will replace the pulling force.

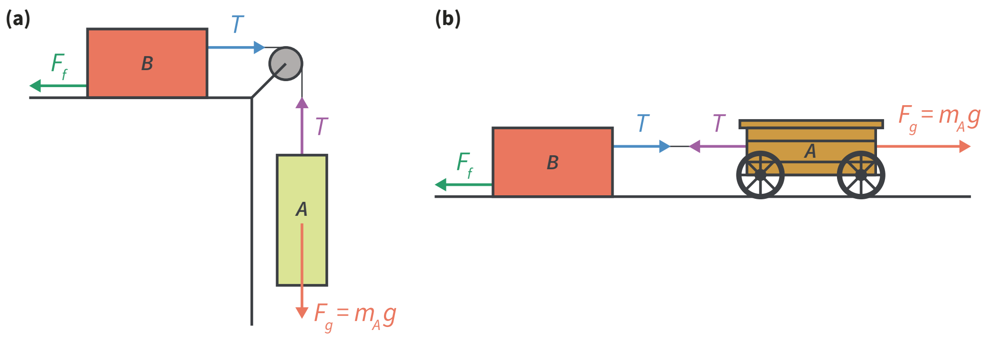


Figure 5 **(a)** The forces involved for a block, *A*, which is hanging and connected to a block, *B*, which is on a horizontal surface. **(b)** For the purpose of calculations, this can be modelled with all forces acting in a horizontal direction.

Connected bodies in contact 3.3.1.6.2

OVERVIEW

When two or more bodies which are in direct contact are pushed (rather than pulled) they will exert contact forces on one another with respect to Newton's third law, being of equal magnitude but in opposite directions. The bodies will always have the same acceleration.

THEORY DETAILS

When two or more connected bodies which are in direct contact are pushed together, they exert contact forces on each other. Figure 6 shows a pushing force, F_x, applied to two blocks which are in contact. This pushing action will cause block *A* to exert a contact force on block *B*, $F_{on\ B\ by\ A}$. As per Newton's third law, block *B* will exert a contact force of equal magnitude and opposite direction on block *A*, $F_{on\ A\ by\ B}$. Friction is not shown in this case.

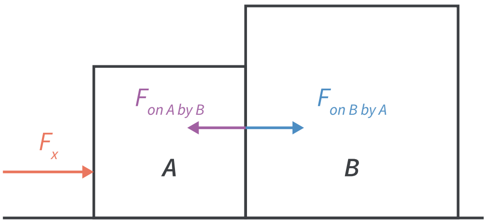


Figure 6 The forces involved when connected bodies are in contact and an external force is applied. The bodies exert forces on each other that are equal in magnitude but opposite in direction. $F_{on\ B\ by\ A}$ is the only force that acts on block *B* whereas block *A* experiences force F_x and $F_{on\ A\ by\ B}$.

Similarly to connected bodies in tension, we can apply Newton's second law to any individual object or to the system of connected bodies as a whole. The way we approach problems involving connected bodies in contact is the same as for connected bodies in tension: the role of the tension force is simply replaced by the contact forces.

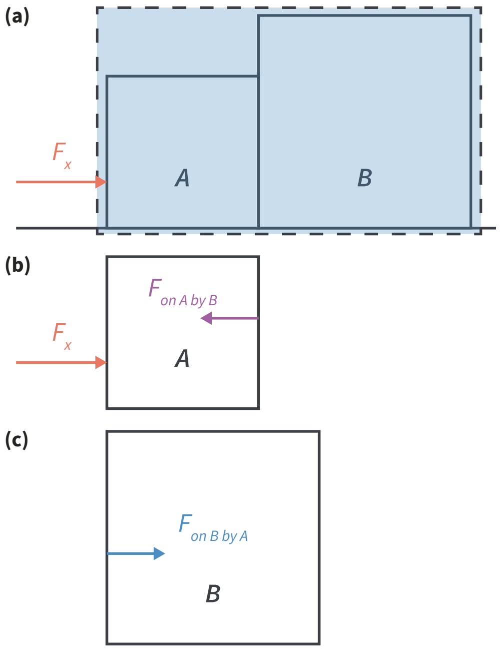


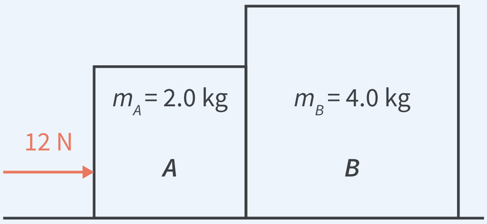
Figure 7 The relevant forces from Figure 6 when we analyse **(a)** the whole system, **(b)** only block *A*, and **(c)** only block *B*.

If we take right as the positive direction in Figure 7, we can see that the relevant equations for considering

- the whole system are $F_{net} = F_x$ and $F_{net} = (m_A + m_B) \times a$.
- only cart *A* are $F_{net} = F_x - F_{on\ A\ by\ B}$ and $F_{net} = m_A \times a$.
- only block *B* are $F_{net} = F_{on\ B\ by\ A}$ and $F_{net} = m_B \times a$.

3 Worked example

Two blocks, *A* and *B*, which have a mass of 2.0 kg and 4.0 kg respectively are in contact and are being pushed on a frictionless surface by a force of 12 N.



a **Calculate the magnitude of 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*.**

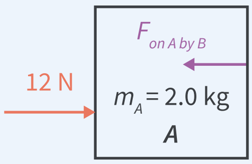
a We do not yet know the contact force which acts on both blocks. We will analyse the whole system (both blocks together) since this does not involve the contact force.

Consider the forces acting on the whole system: $F_{net} = F_x = 12$ N

Apply Newton's second law to the whole system: $F_{net} = (m_A + m_B) \times a \;\; \therefore 12 = (2.0 + 4.0) \times a$

$a = 2.0$ m s^{-2}

b



Apply Newton's second law to block *A*: $F_{net} = m_A \times a = 2.0 \times 2.0 = 4.0$ N

Consider the forces acting on block *A* only: $F_{net} = F_x - F_{on\ A\ by\ B} \;\; \therefore 4.0 = 12 - F_{on\ A\ by\ B}$

$F_{on\ A\ by\ B} = 8.0$ N

c The magnitude of the contact force acting on each block is the same:
$F_{on\ B\ by\ A} = 8.0$ N

Theory summary

- There are three forces that can act on an object on an inclined plane:
  - The force due to gravity – acting vertically down
  - The normal force – acting perpendicular to the inclined plane
  - A friction force (if applicable) – resists motion
- The vector forces can be added to find the net force which will act down the inclined plane with a magnitude given by $F_{net} = mg\sin(\theta) - F_f$ (if friction is applicable).
- Newton's second law can be applied to the whole system or individual components of connected body systems to calculate acceleration and net force.
- Tension is the force on an object by a string, rope or cable.
  - The tension force will have the same magnitude but opposite direction for both objects it is attached to.
  - These two forces will cancel out when working with the whole connected body tension system.
- Connected bodies in contact experience an equal and opposite contact force which cancel each other out when examining the whole system.

USEFUL TIP

When two bodies are in contact on a frictionless surface, the net force on each block will be directly proportional to its mass. So for a 3 kg and 6 kg block, the 6 kg block will have a net force twice as large as the 3 kg block.

KEEN TO INVESTIGATE?

oPhysics 'Static and Kinetic Friction on an Inclined Plane'
https://www.ophysics.com/f2.html

2C Questions

THEORY REVIEW QUESTIONS

Question 1

A mass *m* lies on a plane that is inclined at θ degrees to the horizontal. The component of the force due to gravity that acts parallel down the plane is equal to

A mg.

B $mg\sin(\theta)$.

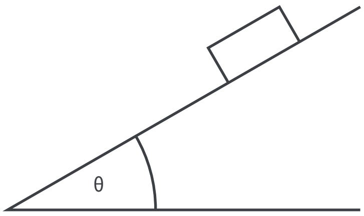
C $mg\cos(\theta)$.

D $\frac{1}{2}mg$.

Question 2

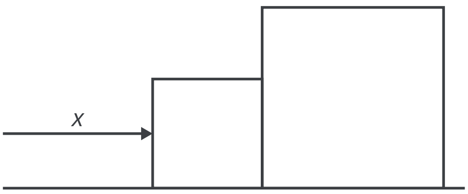
Use arrows to draw all of the forces that act on the box in the diagram as it accelerates down the plane. Assume frictional forces apply. In addition draw the net force, F_{net}, as a dotted line.

Consider the body as a single object.



Question 3

Two solid wooden blocks of different masses are in contact and are being pushed by a constant force *x* on a smooth frictionless surface. The larger mass is twice as heavy as the smaller mass. The net force that acts on each body is



A the same independent of the body's masses.

B twice as much for the smaller mass relative to the larger mass.

C less for the larger mass compared to the smaller mass.

D proportional to the masses of the two blocks.

Question 4

A truck is accelerating whilst pulling a trailer forward connected by a light inextensible string. The tension force in the string acts

A backwards on the truck and forwards on the trailer.

B only backwards on the truck.

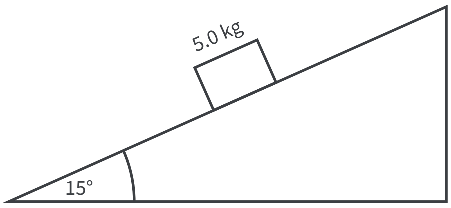
C only forwards on the trailer.

D forwards on the truck and backwards on the trailer.

EXAM-STYLE QUESTIONS

This lesson

Question 5 (5 MARKS)



An object with a mass of 5.0 kg is on a plane inclined at an angle of 15°. The surface is frictionless.

a What is the magnitude of the normal reaction force, F_N, acting on the object? (2 MARKS)

b What is the net force acting on the object? (2 MARKS)

c Calculate the magnitude of the object's acceleration. (1 MARK)

Question 6 (3 MARKS)

Penny is using a tractor of 800 kg to tow a trailer with a mass of 700 kg. The tractor and trailer accelerate at 1.20 m s^{-2}. Ignore the mass of the rope used to tow the trailer and the effects of friction.

a What is the driving force of the tractor? (1 MARK)

b Calculate the tension force between the trailer and the tractor. (2 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 1 Q1/2

Question 7 (4 MARKS)

Howard connects two masses M_1 (0.50 kg) and M_2 (0.25 kg) with a string. The second mass is hanging off the edge of a table and the string runs through a frictionless pulley. M_1 is on a surface with a constant frictional force of 0.50 N and the mass of the string is negligible.

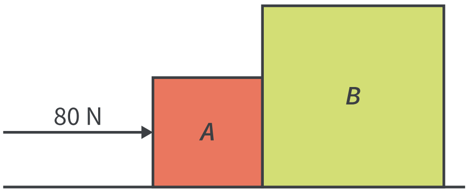
a Calculate the acceleration of M_2. (2 MARKS)

b Calculate the tension in the rope connecting the two masses. (2 MARKS)

Adapted from 2010 VCAA Exam 1 Section A AoS 1 Q3

Question 8 (5 MARKS)

Two blocks, *A* and *B*, which have a mass of 2.0 kg and 6.0 kg respectively are in contact and are being pushed on a frictionless surface by a force of 80 N.



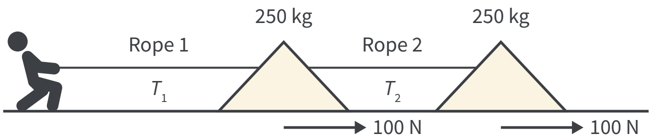
a Find the magnitude of the force on block *A* by block *B*. (3 MARKS)

b What is the direction and magnitude of the force on block *B* by block *A*? (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q8

Question 9 (8 MARKS)

Amy is dragging two miniature pyramids each of mass 250 kg through sand which provides a frictional force of 100 N to each pyramid. T_1 and T_2 represent the tension force that exists in the rope between Amy and the first pyramid and between the two pyramids respectively. A rope will break if its tension force reaches 1800 N.



a What is the magnitude of T_1 when Amy is dragging the pyramids at a constant speed? (1 MARK)

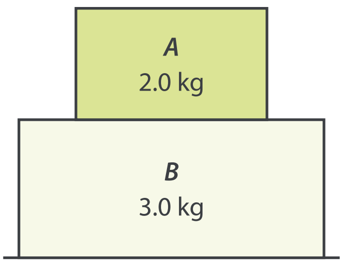
b Amy needs to be home for dinner and accelerates in the direction of motion at 0.25 m s^{-2}. Calculate the magnitude of T_2 and T_1. (4 MARKS)

c Amy's dinner has already been served for her and is beginning to cool down. She increases her acceleration to the point where one of the ropes break. Which rope broke first and what was the magnitude of Amy's acceleration? (3 MARKS)

Adapted from 2012 VCAA Exam 1 Section A AoS 1 Q5

Question 10 (3 MARKS)

Block *B* has a mass of 3.0 kg and sits at rest on top of a table. Block *A* has a mass of 2.0 kg and is resting on top of block *B*.



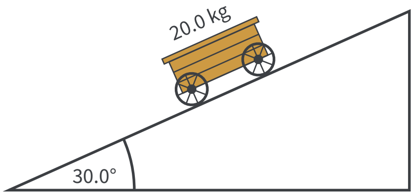
a Calculate the magnitude and direction of the force exerted on block *A* by block *B*. (2 MARKS)

b The table top is then removed and the blocks accelerate downwards at *g*. What is the magnitude of force that block *B* now exerts on block *A*? (1 MARK)

Adapted from 2019 VCAA NHT Exam Section B Q9

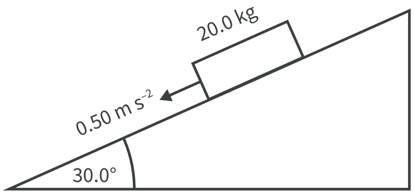
Question 11 (5 MARKS)

A 20.0 kg cart is placed on an inclined plane with θ = 30.0°. Assume that the cart is frictionless.



a What is the magnitude of the acceleration of the cart down the slope? (2 MARKS)

b The cart is replaced with a 20.0 kg lead block. The block accelerates down the slope at 0.50 m s^{-2}.

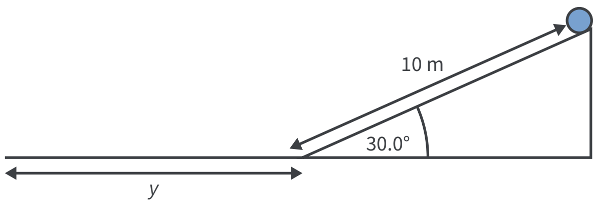


Determine the magnitude of the friction force acting on the lead block. (3 MARKS)

Previous lessons

Question 12 (8 MARKS)

Students Sheldon and Leonard roll a ball down a frictionless hill inclined at 30.0° to the horizontal. The inclined plane of the hill is 10.0 m long. The ball they use has a mass of 0.50 kg and is released from rest. Once the ball reaches the bottom of the hill it rolls onto a surface where there is a constant rolling friction force of 0.75 N which stops the ball after *y* m.

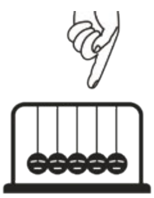


a Calculate the magnitude of the acceleration of the ball as it rolls down the hill. (2 MARKS)

b What is the speed of the ball when it reaches the bottom of the hill? (2 MARKS)

c Calculate the distance, *y*, it takes for the ball to come to a rest when it travels on the flat frictional surface. (3 MARKS)

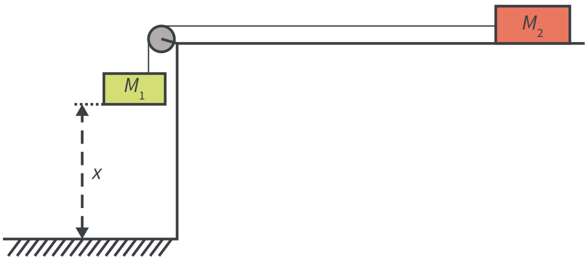
d When the ball is at rest on the horizontal surface it experiences a normal force which can be described as 'the force on the ball by the ground'. If this is considered the 'reaction force', identify the 'action force' in relation to Newton's third law. (1 MARK)



Key science skills

Question 13 (3 MARKS)

Chris and Liam are conducting an experiment where they are attempting to measure the distance M_1 falls in one second using a ruler with gradations every 5 cm. M_1 is connected to M_2 by a light inextensible string over a frictionless surface.



Comment on a random error associated with their distance measurements and two ways in which the effect of random errors can be reduced.

2D BASIC CIRCULAR MOTION

Whenever a body travels in a circle, it is undergoing circular motion. Circular motion is always caused by a net force called the centripetal force. This lesson examines the basics of circular motion. More complex cases of circular motion will be explored in the next few lessons.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Study design key knowledge dot points

- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: $\left(F_{net} = \frac{mv^2}{r}\right)$, including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string
- model natural and artificial satellite motion as uniform circular motion

Key knowledge units

Circular speed	3.3.2.1
Centripetal acceleration	3.3.3.1
Centripetal force	3.3.2.2

Formulas for this lesson

Previous lessons		New formulas
2B	* $F_{net} = ma$	$v = \frac{2\pi r}{T}$
		* $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
		$F_{net} = \frac{mv^2}{r}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

centripetal force the net force causing circular motion which is always directed towards the centre of a body's circular path

frequency the number of cycles completed per unit of time

period the time taken to complete one cycle

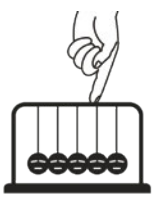
Circular speed 3.3.2.1

OVERVIEW

Circular speed is a quantity that measures the rate of distance travelled around a circular path with respect to time.

THEORY DETAILS

The speed of a body undergoing uniform circular motion can be calculated as distance divided by time. The total distance around a full circle is the circumference ($C = 2\pi r$) and the time taken to complete a revolution is the period (T). This is also the inverse of the frequency $\left(T = \frac{1}{f}\right)$.



From this, we can derive the formula for circular speed:

$$v = \frac{2\pi r}{T}$$

v = circular speed (m s^{-1}), r = path radius (m), T = period (s)

Circular speed is a scalar quantity. The direction of motion (direction of instantaneous velocity) at any point is always tangential to the circular path as seen in Figure 1.

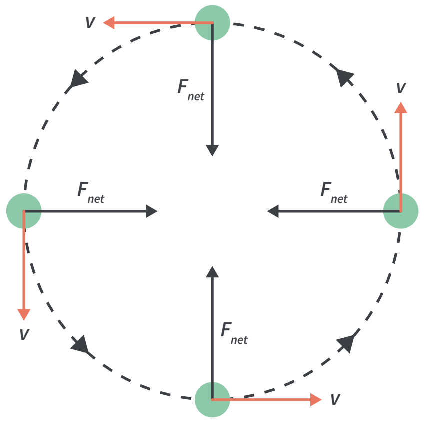


Figure 1 The instantaneous velocity of an object in circular motion is always tangential to the circular path (pointing in the direction of motion). The centripetal force and centripetal acceleration are always directed radially inwards (at a right angle to the direction of motion).

1 **Worked example**

Calculate the speed of a car in km h^{-1} that drives around a roundabout with a radius of 30.0 metres in 15.0 seconds.

r = 30.0 m and T = 15.0 s

$$v = \frac{2\pi r}{T} = \frac{2\pi \times 30.0}{15.0} = 12.57 \text{ m s}^{-1}$$

$$v = 12.57 \times 3.6 = 45.2 \text{ km h}^{-1}$$

Centripetal acceleration 3.3.3.1

OVERVIEW

Centripetal acceleration is a vector quantity that measures the rate of change of the instantaneous velocity when a body travels on a circular path.

THEORY DETAILS

- When a body is undergoing uniform circular motion, it is always accelerating towards the centre of its circular path.
- Centripetal acceleration is always at a right angle to the instantaneous velocity (see Figure 1).
- The radially inward centripetal acceleration causes the direction of motion to continuously change so that it is always tangential to the circular path.

The magnitude of centripetal acceleration can be calculated as follows.

$$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$$

a = centripetal acceleration magnitude (m s^{-2}), v = circular speed (m s^{-1}), r = path radius (m), T = period (s)

Note that any body undergoing circular motion is accelerating even if it has a constant speed. This is because the **velocity** of the body must be changing since its direction changes. In VCE Physics we will only ever deal with circular motion at constant speeds (known as uniform circular motion).

2 Worked example

Calculate the magnitude of the centripetal acceleration of a car that drives around a roundabout with a radius of 30.0 m in 15.0 seconds.

a **using $a = \frac{4\pi^2 r}{T^2}$.**

b **using $a = \frac{v^2}{r}$ with values calculated in Worked example 1.**

a $a = \frac{4\pi^2 r}{T^2} = \frac{4 \times \pi^2 \times 30.0}{15.0^2} = 5.26\ \text{m s}^{-2}$

b From Worked example 1, $v = 12.57\ \text{m s}^{-1}$ and $r = 30.0$ m.

$a = \frac{v^2}{r} = \frac{12.57^2}{30.0} = 5.26\ \text{m s}^{-2}$

Centripetal force 3.3.2.2

OVERVIEW

The centripetal force is the net force that causes a body to undergo circular motion. It always points radially inwards towards the centre of the circular path.

THEORY DETAILS

Centripetal force is the name for the **net force** when a body is in uniform circular motion. It is not an individual physical force acting on a body, but the vector sum of all other forces.

When a car is driving in a circle, the centripetal force is the net force caused by friction between the car tyres and the road. When swinging earphones in a vertical circle, the centripetal force is the net force of the tension in the cord and the gravitational force. We can also model orbital motion as circular motion. In this case, the centripetal force is the net force caused by the gravitational force. Orbital motion is covered in more detail in Chapter 5.

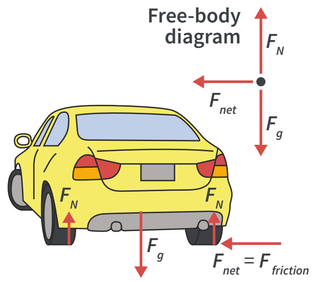


Figure 2 The centripetal force acting on a car undergoing circular motion on a flat track is caused by friction between the tyres and the road

By Newton's second law, we know that $F_{net} = ma$. Given that a body in circular motion is accelerating radially inwards, there will be a net force on the body radially inwards.

By substituting the formula for centripetal acceleration $\left(a = \frac{v^2}{r}\right)$ into Newton's second law we can derive the equation for centripetal force:

$$F_{net} = \frac{mv^2}{r} = m\frac{4\pi^2 r}{T^2}$$

F_{net} = centripetal force (N), m = mass of body (kg), v = circular speed (m s^{-1}), r = path radius (m), T = period (s)

Like the centripetal acceleration, the centripetal force **always** points radially inwards. This means it points directly to the centre of an object's circular path.

3 Worked example

Calculate the magnitude of the centripetal force of a 700 kg car that drives around a roundabout with a radius of 30.0 m in 15.0 seconds.

$r = 30.0$ m, $m = 700$ kg, $T = 15.0$ s

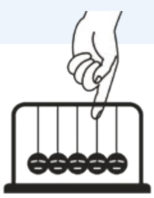
$F = m\frac{4\pi^2 r}{T^2} = 700 \times \frac{4 \times \pi^2 \times 30.0}{15.0^2} = 3.68 \times 10^3\ \text{N}$

OR

From Worked example 1, $v = 12.57\ \text{m s}^{-1}$

$r = 30.0$ m, $m = 700$ kg

$F = \frac{mv^2}{r} = \frac{700 \times 12.57^2}{30.0} = 3.68 \times 10^3\ \text{N}$



Theory summary

	Formula	Direction	Description
Circular speed/ instantaneous velocity	$v = \frac{2\pi r}{T}$	No direction/tangential	Rate of change of position around a circular path
Centripetal acceleration	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$	Radially inwards	Rate of change of instantaneous velocity
Centripetal force	$F_{net} = \frac{mv^2}{r} = m\frac{4\pi^2 r}{T^2}$	Radially inwards	Net force that causes circular motion

KEEN TO INVESTIGATE?

YouTube video: Crash Course – Uniform Circular Motion
https://youtu.be/bpFK2VCRHUs

YouTube video: The Science Asylum – Centrifugal Force Does NOT Exist
https://youtu.be/zHpAifN_2Sw

2D Questions

THEORY REVIEW QUESTIONS

Question 1

Identify the correct directions of circular speed, centripetal acceleration and centripetal force.

	Circular speed	Centripetal acceleration	Centripetal force
A	Tangential	Radially inwards	Radially inwards
B	No direction	Radially inwards	Radially inwards
C	Tangential	No direction	Radially inwards
D	Radially inwards	Tangential	Tangential

Question 2

Instantaneous velocity in circular motion can be calculated by

A dividing the total circumference of the circular path by the time taken to complete one revolution.

B multiplying 2π by the radius of the circle and the time taken to complete one revolution.

C dividing the total circumference of the circular path by the time taken to complete one revolution and including the tangential direction.

D multiplying 2π by the radius of the circle and the time taken to complete one revolution and including the tangential direction.

Question 3

The best description of the centripetal force is

A the product of a body's mass and its acceleration.

B the net force for objects undergoing circular motion, which points radially inwards.

C the force that points radially inwards for objects undergoing circular motion.

D the force that points in the direction of motion for objects undergoing circular motion.

Question 4

When does a car **not** experience a centripetal acceleration?

A When it speeds up along a straight track

B When it travels around a roundabout at constant speed

C When it turns around a corner following a circular path at a constant speed

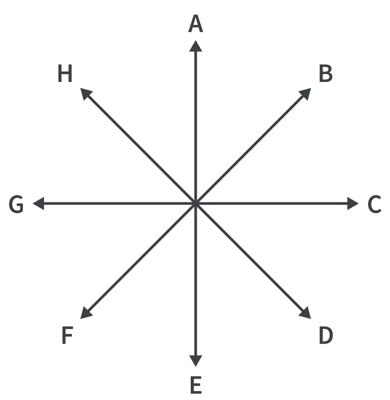
D None of the above

EXAM-STYLE QUESTIONS

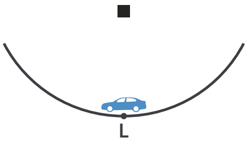
This lesson

Question 5 (6 MARKS)

Identify the direction of the centripetal force of the body undergoing circular motion. The centre of motion in each case is indicated with a small black square.

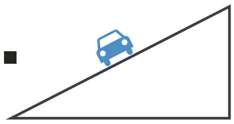


a



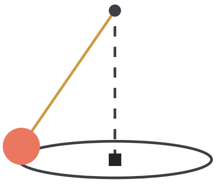
(1 MARK)

b



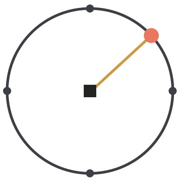
(1 MARK)

c



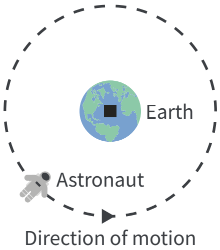
(1 MARK)

d



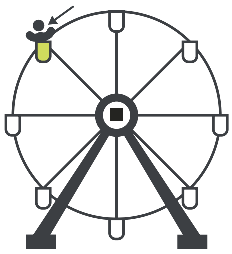
(1 MARK)

e



(1 MARK)

f

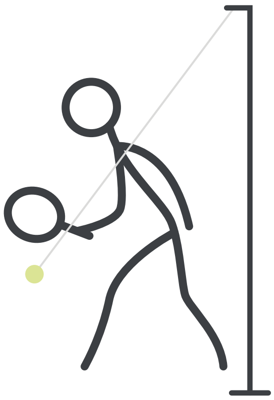


(1 MARK)

Adapted from 2013 VCAA Exam Section A Q5 and 2009 VCAA Exam 1 Section A Q13

Question 6 (1 MARK)

In a game of totem tennis, a tennis ball travels around the central pole at a speed of 16 m s^{-1}. The ball travels a circular path with a radius of 1.5 m. The tennis ball has a mass of 60 grams. Calculate the magnitude of the centripetal acceleration of the ball.



Question 7 (1 MARK)

A bus with a mass of 15 000 kg drives around a roundabout with a 45.0 m radius over a period of 30.0 seconds. Calculate the magnitude of the centripetal force on the bus.

Question 8 (2 MARKS)

A student runs around a circular track with a radius of 50.0 m at a speed of 8.00 m s^{-1}. The student has a mass of 55.0 kg.

a Calculate the magnitude of the student's centripetal acceleration. (1 MARK)

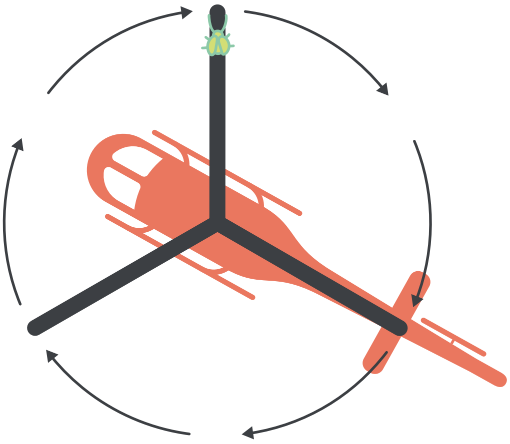
b Calculate the magnitude of the centripetal force acting on the student. (1 MARK)

Question 9 (3 MARKS)

A beetle is trying to cling on to the end of a rotor blade of a helicopter rotating at a constant speed. The helicopter rotor undergoes 8.00 revolutions per second. The rotor blades are 12.0 m long.

a Calculate the circular speed that the beetle must theoretically endure. (2 MARKS)

b Given that the beetle is unable to hold on to the blade, in what direction will it travel if it lets go at the position indicated in the diagram? (1 MARK)



Question 10 (3 MARKS)

A 600 kg car drives around a roundabout with a 60 m radius at 36 km h^{-1}.

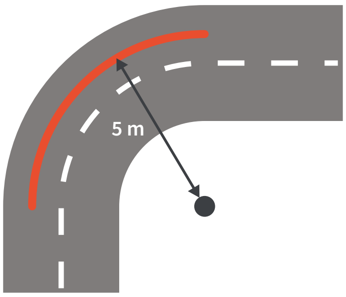
a Calculate the magnitude of the acceleration of the car. (2 MARKS)

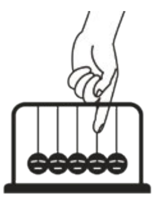
b Calculate the magnitude of the centripetal force experienced by the car. (1 MARK)

Adapted from 2009 VCAA Exam 1 Section A Q3

Question 11 (3 MARKS)

Calculate how long it takes for a car to turn right around a 90° corner with a radius of 5.0 m if the car is driving at 15 m s^{-1}. Assume the car takes a circular path.





Question 12 (7 MARKS)

Mars (radius 3.00×10^6 m) has two moons called Deimos and Phobos. Deimos orbits Mars 2.30×10^7 m from the surface of the planet. It takes 30.0 hours for Deimos to complete a circular orbit of Mars.

a Calculate the orbital speed of Deimos. (3 MARKS)

b Calculate the magnitude of the orbital acceleration of Deimos. (1 MARK)

c Phobos takes 8.00 hours to orbit Mars, and orbits at a speed of 2.00×10^3 m s^{-1}. Calculate the orbital height of Phobos above the surface of Mars. (3 MARKS)

Question 13 (2 MARKS)

Hafsah attaches a 0.30 kg ball to a 0.80 metre long string. The string will snap if the tension is greater than or equal to 3.0 N. Hafsah then makes the ball move in a horizontal circle on the frictionless floor, slowly increasing the ball's speed. Calculate the maximum speed the ball can reach before the string will break.

Adapted from 2012 VCAA Exam 1 Section A Q7

Previous lessons

Question 14 (4 MARKS)

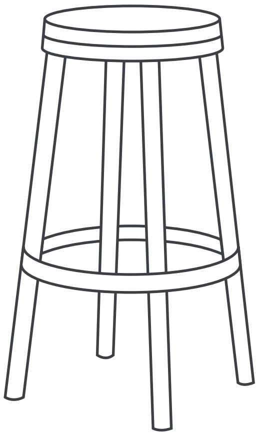
A 1.5 kg box starts at rest on a smooth ramp angled at 15° behind a stationary truck. The box slides a distance of 2.0 metres down the ramp. Calculate the speed of the box when it reaches the bottom of the ramp.

Question 15 (3 MARKS)

There is a force that acts upwards on each of the four legs of a symmetrical 20.0 kg stool when it is placed on the ground.

a Identify the name of this force. (1 MARK)

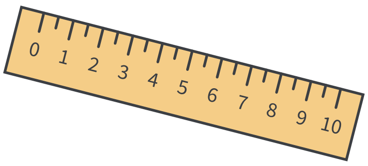
b Calculate the magnitude of the force on one leg. (2 MARKS)



Key science skills

Question 16 (2 MARKS)

Aarushi is measuring the radius of a circular model train track to calculate the train's circular speed. She uses this ruler and measures the radius to be seven centimetres. Explain how to identify the uncertainty in this measuring device and state the uncertainty.



2E BANKED CIRCULAR MOTION

Have you ever wondered why cycling events at the Olympics take place on banked tracks in a velodrome? This lesson explores the physics of circular motion on banked tracks and circular motion with conical pendulums.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Study design key knowledge dot point

- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: $F_{net} = \frac{mv^2}{r}$, including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string

Key knowledge units

Banked tracks	3.3.2.3.1
Conical pendulums	3.3.2.3.2

Formulas for this lesson

Previous lessons		New formulas
2B	$F_g = mg$	$F_N = \sqrt{F_{net}{}^2 + F_g^2}$
2D	$F_{net} = \frac{mv^2}{r}$	$F_{net} = F_N \sin(\theta) = F_g \tan(\theta)$
		$v = \sqrt{rg\tan(\theta)}$

Definitions for this lesson

conical pendulum a mass on the end of a string which undergoes horizontal circular motion

design speed the speed on a banked track for which there is no sideways frictional force acting on the vehicle

Banked tracks 3.3.2.3.1

OVERVIEW

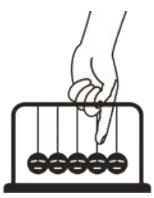
Banked tracks are curved sections of a track for a vehicle commonly used in races. They are useful because of a phenomenon called the 'design speed'. A vehicle travelling at the design speed of a banked track does not require a friction force between the tyres and the road to provide the centripetal force.

THEORY DETAILS

Forces

In most real-world circumstances, a vehicle undergoing circular motion on a banked track experiences three forces:

- The force due to gravity (F_g)
- A normal force (F_N)
- A sideways frictional force – not applicable to calculations in VCE Physics



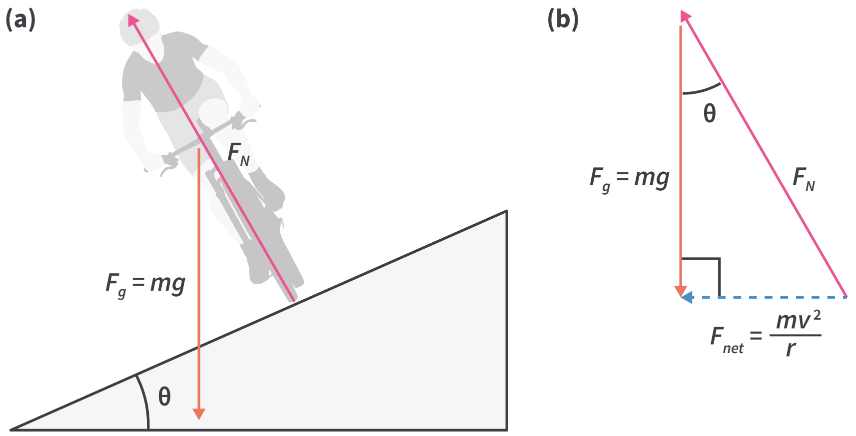


Figure 1 **(a)** A cyclist riding in a circle on a banked track at the design speed. **(b)** There is no sideways frictional force so the centripetal force is equal to the horizontal component of the normal force. The vertical component of the normal force is balanced by the force due to gravity.

The net force is the **centripetal force** $\left(F_{net} = \frac{mv^2}{r}\right)$. It always points **horizontally** towards the centre of the circular path of the vehicle (**not** the centre of the track at ground level).

When a vehicle is travelling at a certain speed, known as the 'design speed' (explored in the next section), there will be no sideways force exerted on the vehicle by the track.
This condition will always apply to calculation questions in VCE Physics. In this case, the relevant forces on the vehicle are as shown in Figure 1.

USEFUL TIP

The centripetal force is not a single force for banked circular motion. It is the resultant (net) force due to the normal force and the force due to gravity. Therefore if we are asked to draw 'the forces acting on the vehicle' in banked circular motion, we should not draw the centripetal force – we should draw only the normal force and the force due to gravity. However, it is common for exam questions to ask us to draw the net force as well.

If we apply trigonometry to the force triangle in Figure 1 we can derive the following formulas for the net/centripetal force.

$$F_{net} = F_N \sin(\theta) = F_g \tan(\theta)$$

F_{net} = net/centripetal force (N), F_N = normal force (N), θ = angle of banked track (°), F_g = force due to gravity (N)

Similarly, we can apply Pythagoras' theorem to the force triangle in Figure 1:

$$F_N = \sqrt{{F_{net}}^2 + F_g^2}$$

F_N = normal force (N), F_{net} = net/centripetal force (N), F_g = force due to gravity (N)

USEFUL TIP

Do not confuse the relationships between forces for banked circular motion with the relationships that apply to objects on inclined planes (lesson 2C). Although the diagrams look similar, the relationships between the forces for banked circular motion are **different**.

- The normal force is the hypotenuse of the force triangle for banked circular motion.
- The force due to gravity is the hypotenuse of the force triangle for objects on inclined planes.

Design speed

For a track banked at an angle θ, there is a corresponding speed for which the centripetal force is generated solely from the horizontal component of the normal force (as in Figure 1). We will generally refer to this speed as the 'design speed', but VCE exams usually describe it is as the speed at which there is 'no sideways force'.

Using the force triangle in Figure 1, we can relate the design speed of a banked track to the track's radius and angle of bank:

$$\tan(\theta) = \frac{F_{net}}{F_g} = \frac{\frac{mv^2}{r}}{mg} = \frac{v^2}{rg}$$

This can be rearranged to give the design speed formula:

> $v = \sqrt{rg\tan(\theta)}$
>
> **v = design speed (m s^{-1}), r = radius of circular path (m), g = gravitational acceleration (m s^{-2}), θ = angle of banked track (°)**

From this formula, we can conclude:

- As the slope angle increases, the design speed increases
- As the radius of the circular path increases, the design speed increases

1 **Worked example**

Calculate the speed required for there to be no sideways friction force when an athlete cycles on a circular track with a 25 m radius banked at a 35° angle.

$v = \sqrt{rg\tan(\theta)}$

$v = \sqrt{25 \times 9.8 \times \tan(35°)}$

$v = 13$ m s^{-1}

Conical pendulums 3.3.2.3.2

OVERVIEW

Conical pendulums are set up like a standard pendulum (a mass hanging from a string) which is then made to undergo horizontal circular motion. It is called a conical pendulum because the string traces out the curved surface of a cone as the mass completes a revolution. While VCE Physics exams do not use the term 'conical pendulum' (they usually describe 'a ball on a string moving in a horizontal circle'), it is a convenient term for our purposes. Conical pendulums can be analysed in the same way as circular motion on banked tracks with respect to the forces and speed.

THEORY DETAILS

Another important kind of circular motion that involves an angle is the conical pendulum. This is when an object undergoes horizontal circular motion while it is suspended from a string with a negligible mass. An example of this is the motion of the ball in a game of totem tennis (Figure 2).

An object undergoing circular motion on the end of a string will experience two forces (when ignoring air resistance):

- The force due to gravity (F_g)
- A tension force (T) – this has the same role as the normal force for circular motion on banked tracks

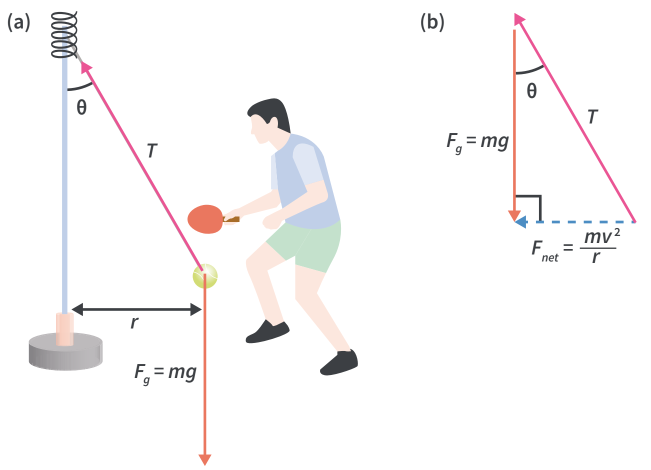


Figure 2 **(a)** The forces on a conical pendulum are tension and the force due to gravity. **(b)** The centripetal force is equal to the horizontal component of the tension force. The vertical component of the tension force is balanced by the force due to gravity.

The formulas that relate the forces for conical pendulums are the same as those for the motion of vehicles on banked circular tracks, but we replace the normal force with the tension force:

- $F_{net} = T\sin(\theta) = F_g \tan(\theta)$
- $T = \sqrt{{F_{net}}^2 + F_g^2}$

Similarly the formula for speed of the object on the end of the string is the same as the design speed formula for a banked track: $v = \sqrt{rg\tan(\theta)}$.

USEFUL TIP

If using equations involving trigonometry for conical pendulum questions, make sure to use the angle between the string and the vertical line to the centre of the circular path.

2 **Worked example**

A mass is swung on a string from above in a horizontal circle with a radius of 1.0 m. It has a mass of 400 g and a speed of 1.3 m s^{-1}. The string makes an angle of 9.8° to the vertical. Calculate the tension in the string.

Method 1

$$T = \sqrt{{F_{net}}^2 + F_g^2}$$

$$T = \sqrt{\left(\frac{mv^2}{r}\right)^2 + (mg)^2}$$

$$T = \sqrt{\left(\frac{0.400 \times 1.3^2}{1.0}\right)^2 + (0.400 \times 9.8)^2}$$

$T = 4.0$ N

Method 2

$$T = \frac{F_{net}}{\sin(\theta)}$$

$$T = \frac{mv^2}{r\sin(\theta)}$$

$$T = \frac{0.400 \times 1.3^2}{1.0 \times \sin(9.8)}$$

$T = 4.0$ N

Method 3

$$T = \frac{F_g}{\cos(\theta)}$$

$$T = \frac{mg}{\cos(\theta)}$$

$$T = \frac{0.400 \times 9.8}{\cos(9.8)}$$

$T = 4.0$ N

Theory summary

	Banked track	Conical pendulum
Description	A vehicle experiences a gravitational force, normal force, and a friction force (if not at the design speed). These add to form the net force, known as the centripetal force.	A mass undergoing horizontal circular motion experiences a gravitational force and tension. These add to form the net force, known as the centripetal force.
Speed	Design speed is calculated by $v = \sqrt{rg\tan(\theta)}$ Other speeds are possible at the same radius, but would require a frictional force.	Speed of mass is calculated by $v = \sqrt{rg\tan(\theta)}$ This is the only speed possible for an object in circular motion at that radius.
Hypotenuse of force triangle	The normal force is always the hypotenuse of the force triangle. $F_N = \sqrt{{F_{net}}^2 + F_g^2}$ $F_N = \frac{mg}{\cos(\theta)}$ $F_N = \frac{mv^2}{r\sin(\theta)}$	The tension is always the hypotenuse of the force triangle. $T = \sqrt{{F_{net}}^2 + F_g^2}$ $T = \frac{mg}{\cos(\theta)}$ $T = \frac{mv^2}{r\sin(\theta)}$

KEEN TO INVESTIGATE?

oPhysics 'Conical Pendulum: 3D' simulation
https://www.ophysics.com/f5.html

oPhysics 'The Conical Pendulum' simulation
https://www.ophysics.com/f4.html

2E Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following forces is **not** expected to be present in a banked track problem?

A Force due to gravity

B Friction force

C Normal force

D Tension

Question 2

Which of the following forces is **not** expected to be involved in a conical pendulum problem?

A Tension

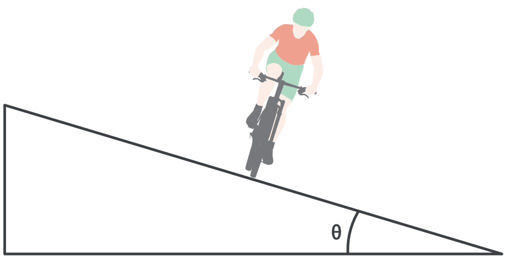
B Normal force

C Force due to gravity

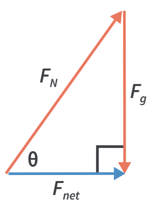
D Centripetal force

Question 3

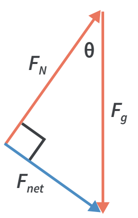
Which of the following force triangles correctly shows the net force and the forces acting on the bicycle?



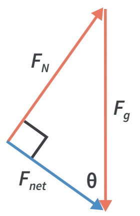
A



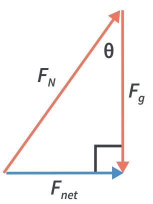
B



C



D



Question 4

Which of the following statements is true regarding banked circular motion questions?

A Bodies in banked tracked problems are not accelerating.

B We only consider bodies with constant speeds in circular motion.

C The friction force is always present in a banked track question.

D Different equations need to be used to calculate the speed in banked track and conical pendulum questions.

EXAM-STYLE QUESTIONS

This lesson

Question 5 (4 MARKS)

A cyclist rides around the banked track of a velodrome angled at 35° to the horizontal in a circular path with a radius of 40 m.

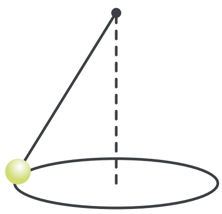
a Calculate the speed they should ride at so that they do not have to experience a sideways friction force to maintain this path. (2 MARKS)

b Calculate the angle the banked track would have to be for there to be no sideways friction force if they rode at 20 m s^{-1}. (2 MARKS)

Adapted from 2017 VCAA Exam Section B Q7

Question 6 (7 MARKS)

A 1.2 kg mass is swung on the end of a string at a constant speed of 2.0 m s^{-1}. The radius of the circular path is 60 cm. The string can be made longer or shorter if necessary.



a Draw a diagram indicating the forces acting on the mass. Draw the net force with a dashed line. (3 MARKS)

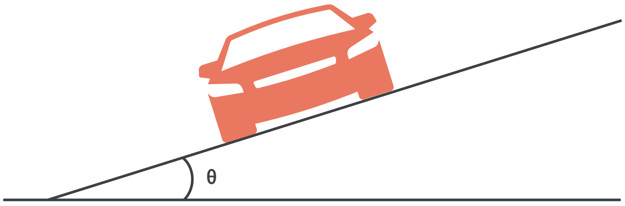
b Calculate the tension in the string. (2 MARKS)

c The speed of the mass is now changed. Calculate the angle from the vertical to the string required for the mass to have a constant speed of 1.5 m s^{-1}. The radius of the circular path is still 60 cm. (2 MARKS)

Adapted from 2016 VCAA Exam Section A Q2

Question 7 (9 MARKS)

A 2000 kg car drives around a banked corner of a racing track angled at 50° to the horizontal.



a Calculate the radius of the 50° path that would allow them to drive without a sideways friction force at a constant speed of 40 m s^{-1}. (2 MARKS)

b Calculate the speed that would allow them to drive on the 50° path with an 80 m radius without experiencing a sideways friction force. (2 MARKS)

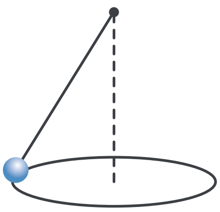
c Use arrows with solid lines to show the forces acting on the car as it drives around the track in the situation described in part **b**. In addition, use a dashed arrow to show the net force acting on the car. Values are not required. (2 MARKS)

d Calculate the magnitude of the net force on the car as it drives on the 50° banked track at a speed of 40 m s^{-1} on a path with an 80 m radius. (1 MARK)

e Calculate the ideal angle of the banked track for a 40 m s^{-1} speed and path with a radius of 80 m. (2 MARKS)

Question 8 (4 MARKS)

A 300 g yo-yo is swung in a horizontal circle from above. The length of the yo-yo string is 0.70 m, and the radius of the circle is 0.40 m.



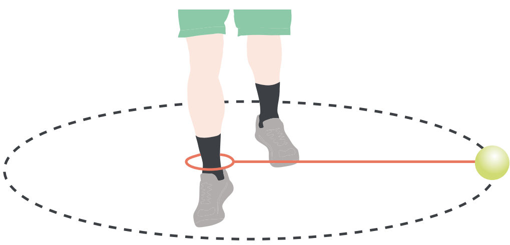
a Calculate the magnitude of the net force on the yo-yo. (2 MARKS)

b Calculate the tension in the string. (2 MARKS)

Previous lessons

Question 9 (3 MARKS)

A child is playing with a swing ball (a toy where someone jumps with one foot over a rod connected to a mass that is spun in a circle by the other foot). The rod has a length of 60 cm and the ball at the end has a mass of 0.20 kg. The ball takes 1.4 seconds to complete one horizontal revolution.

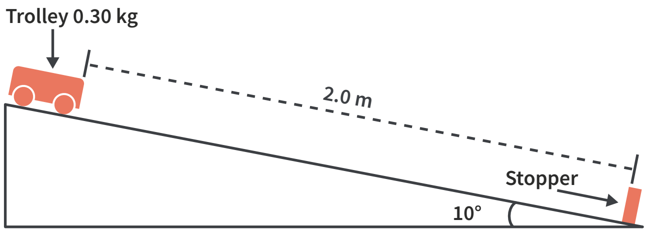


a Calculate the magnitude of the centripetal acceleration of the ball. (2 MARKS)

b Calculate the magnitude of the centripetal force experienced by the ball. (1 MARK)

Question 10 (3 MARKS)

A 0.30 kg trolley rolls down a 2.0 m frictionless ramp angled at 10° to the horizontal until it hits a stopper at the bottom of the ramp. The trolley is released from rest. Calculate the speed of the trolley as it hits the stopper.



Key science skills

Question 11 (9 MARKS)

Georgina is analysing the design speed of a small car around several banked tracks with different radii. She measures the following data. The uncertainty in radius measurements is ±1.0 m.

Radius r (m)	Velocity v (m s^{-1})	v^2 (m^2 s^{-2})
5.0	5.32	
10	7.52	
15	9.21	
20	10.6	
25	11.9	
30	13.0	

a Calculate the values of v^2 (the last column of the table) to three significant figures. (1 MARK)

b Plot a graph of v^2 versus r including appropriate uncertainties. Draw a line of best fit on the graph. (5 MARKS)

c Use the gradient of the line of best fit from part **b** to calculate the angle of the track given that the relationship between radius and velocity is $v^2 = rg\tan(\theta)$. (3 MARKS)

Adapted from 2019 NHT VCAA Exam Section B Q8

2F VERTICAL CIRCULAR MOTION

If you have ever swung a bucket of water in a vertical circle you might know that the bucket can be momentarily upside down without the water coming out. Similarly, a roller coaster can complete a loop-the-loop without being supported by an upwards force. In this lesson we bring circular motion into the context of vertical motion. This combines what we have learned about circular motion with our knowledge of gravitational, normal and tension forces.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Study design key knowledge dot point

- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only)

Key knowledge units

Forces in vertical circular motion	3.3.4.1
Zero normal force in vertical circular motion	3.3.4.2

Formulas for this lesson

Previous lessons		New formulas
2B	$F_g = mg$	$v = \sqrt{gr}$ when $F_N = 0$
2D	$^*a = \frac{v^2}{r}$	
2D	$F_{net} = \frac{mv^2}{r}$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Forces in vertical circular motion 3.3.4.1

OVERVIEW

The study of vertical circular motion requires the careful addition and subtraction of forces. The normal (or tension) force and the force due to gravity result in the centripetal force which must point towards the centre of the circle.

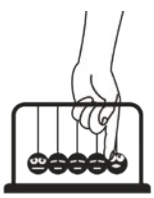
THEORY DETAILS

In VCE Physics, the types of scenarios we have to consider are:

- objects on the top and outside of vertical circles (see Figure 1).
- objects on the top and inside of vertical circles (see Figure 2).
- objects on the bottom and inside of vertical circles (see Figure 3).

All three scenarios are governed by the same rules where the centripetal force, $F_{net} = \frac{mv^2}{r}$, is the result of the force due to gravity, F_g, and the normal force, F_N. For simplicity, all equations in this lesson will treat the forces as magnitudes, meaning F_{net}, F_g, and F_N will always be positive values.

The direction of the normal force will always act on the object away from the track and the force due to gravity always acts downwards.



Forces at the top and outside of vertical circles

This situation is often associated with carts, cars, and roller coasters.

For an object at the top and outside of a vertical circular track:

- the normal force acts upwards.
- the net force, $\frac{mv^2}{r}$, is downwards (towards the centre of the circle).
- $\frac{mv^2}{r} = F_g - F_N$

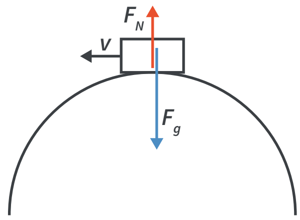
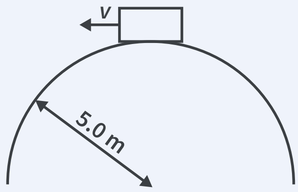


Figure 1 An object moving on the top and outside of a vertical circle

1 **Worked example**

A cart of mass 10 kg is moving over a circular track with a radius of 5.0 m at a speed of 6.0 m s^{-1}. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Calculate the magnitude of the normal force when the cart is at the top of the track.



$\frac{mv^2}{r} = F_g - F_N = mg - F_N \;\therefore \frac{10 \times 6.0^2}{5} = 10 \times 9.8 - F_N$

$F_N = 26$ N

(Notice that the normal force in this case is less than when the cart is at rest on a horizontal surface, which would be 98 N).

Forces at the top and inside of vertical circles

This situation is often associated with roller coasters completing loop-the-loops or objects swinging on a string.

In situations involving strings the tension force is used instead of the normal force. Although they are distinct forces, in these situations they can be treated as mathematically equivalent.

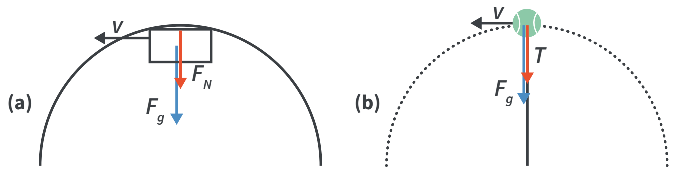


Figure 2 **(a)** An object moving on the top and inside of a vertical circle. **(b)** This is equivalent to a ball on a string at the top of its vertical circular motion.

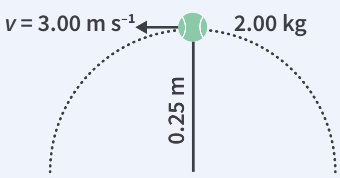
For an object at the top and inside of a verticle circular track, or at the top of vertical circular motion while attached to a string:

- the normal/tension force acts downwards.
- the net force, $\frac{mv^2}{r}$, is downwards (towards the centre of the circle).
- $\frac{mv^2}{r} = F_g + F_N$ **OR** $\frac{mv^2}{r} = F_g + T$

2 **Worked example**

A 2.00 kg ball is being spun at a velocity of 3.00 m s^{-1} on the end of a rope that is 0.25 m long. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Calculate the tension force on the ball by the rope.



$\frac{mv^2}{r} = F_g + T = mg + T \;\therefore \frac{2.00 \times 3.00^2}{0.25} = 2.00 \times 9.8 + T$

$T = 52.4 = 52$ N

Forces at the bottom and inside of vertical circles

This situation is often associated with carts, cars, roller coasters, or objects swinging on a string.

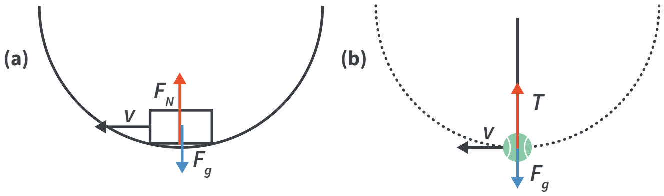


Figure 3 **(a)** An object at the bottom and inside of a vertical circle. **(b)** This is equivalent to a ball on a string at the bottom of its vertical circular motion.

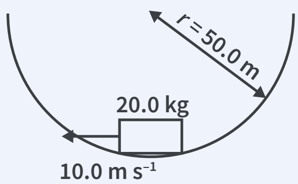
For an object at the bottom and inside of a vertical circular track, or at the bottom of vertical circular motion while attached to a string:

- the normal/tension force acts upwards.
- the net force, $\frac{mv^2}{r}$, is upwards (towards the centre of the circle).
- $\frac{mv^2}{r} = F_\mathrm{N} - F_\mathrm{g}$ OR $\frac{mv^2}{r} = T - F_\mathrm{g}$

3 **Worked example**

A block of mass 20.0 kg slides down a circular dip of radius 50.0 m with no friction and reaches a speed of 10.0 m s^{-1}. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Calculate the normal force on the object when it is at the bottom of the dip.



$\frac{mv^2}{r} = F_N - F_g = F_N - mg \;\therefore\; \frac{20.0 \times 10.0^2}{50.0} = F_N - 20.0 \times 9.8$

$F_N = 236 = 2.4 \times 10^2$ N

(Notice that the normal force in this case is greater than when the block is at rest on a horizontal surface, which would be 196 N).

Zero normal force in vertical circular motion 3.3.4.2

OVERVIEW

In vertical circular motion, when the centripetal force **at the top of the circle** is equal to the force due to gravity, the magnitude of the normal (or tension) force acting on the object is zero. This leads to a feeling of 'zero gravity' for a person undergoing such motion.

THEORY DETAILS

Consider the force equations for the motion of an object **at the top** of a circle (either on the outside or inside):

$\frac{mv^2}{r} = mg + F_N$ OR $\frac{mv^2}{r} = mg + T.$

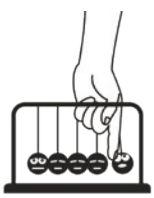
When the track does not exert a normal force ($F_\mathrm{N} = 0$) or when there is no tension force ($T = 0$), we have: $\frac{mv^2}{r} = mg$

This leads to the following relationship.

> $v = \sqrt{gr}$
>
> **v = speed (m s^{-1}), r = radius (m), g = acceleration due to gravity (m s^{-2})**

This formula applies when the normal or tension force is zero for any object at the top of its vertical circular motion, whether the object is outside or inside a loop, or on a string. However, the relevance of this speed and the words which can be used to describe it are different in each situation.

- For an object at the top and **outside** of a vertical circle, it is the **maximum speed** at which the object will remain in contact with the track.
- For an object at the top and **inside** of a vertical circle, it is the **minimum speed** at which the object will remain in contact with the track (or the minimum speed at which the string will remain in tension).



A person undergoing this motion may report having felt ‘zero gravity’. This is because we are used to associating gravity with the normal force, which has the same magnitude as the gravitational force when we are at rest on the ground. It is important to understand that:

- the force due to gravity is **not** actually zero in this case.
- this feeling is a result of the normal force being zero.

4 **Worked example**

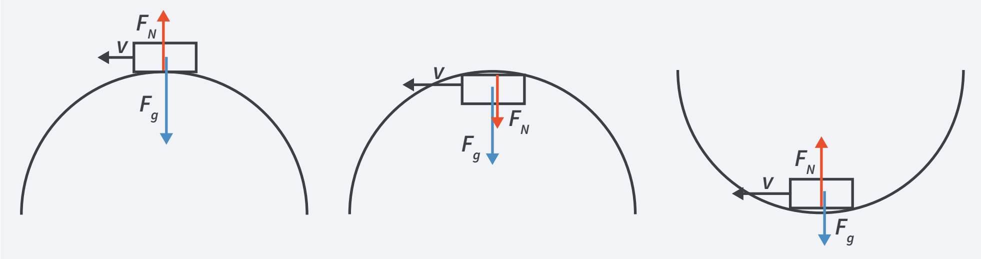
A car drives over a hill that has a radius of 40 m. Calculate the maximum speed the car can travel without leaving the road. Take the acceleration due to gravity to be 9.8 m s^{-2}.

By asking for the maximum speed without leaving the road, we know to use the zero normal force equation.

$v = \sqrt{gr} = \sqrt{9.8 \times 40}$

$v = 19.79 = 20$ m s^{-1} is the maximum speed the car can travel without leaving the road.

Theory summary



$\frac{mv^2}{r} = F_g - F_N$ $\quad$ $\frac{mv^2}{r} = F_g + F_N$ $\quad$ $\frac{mv^2}{r} = F_N - F_g$

- The speed corresponding with a zero normal force at the top of vertical circular motion can be found using $v = \sqrt{gr}$.
- On Earth, the term ‘zero gravity’ can refer to experiencing a lack of a normal force, rather than the absence of a gravitational force.

KEEN TO INVESTIGATE?

YouTube video: Flipping Physics – Minimum Speed for Water in a Bucket Revolving in a Vertical Circle
https://youtu.be/TIBcntHCxjQ

2F Questions

THEORY REVIEW QUESTIONS

Question 1

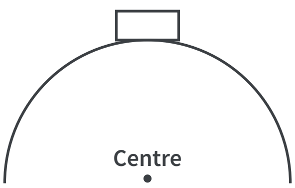
Identify the direction of the **net** force in this scenario assuming the cart is moving along the track and does not leave the track.

A Left

B Right

C Up

D Down



Question 2

The feeling of ‘zero gravity’ for a person is caused by

A the lack of gravity present at the person’s location.

B the person not experiencing a normal force.

C the person rejecting the existence of gravity.

D the person experiencing two balanced forces that hold it perfectly in place.

Question 3

In which of the following situations is there going to be neither tension nor normal force?

A A cart is travelling at a speed inside the top of a loop where the centripetal force and the force on the cart due to gravity are equal.

B A car goes over a hill, which can be approximated to a circle, and is on the verge of leaving the road.

C A stone is connected to a rope and is spun vertically. At the top of the spin it is travelling at a speed fast enough to balance the force due to gravity on the stone with its centripetal force.

D All of the above.

Question 4

The normal force acting on an object at rest on a horizontal surface is 100 N. Compare the magnitude of the normal force for the same object when it is moving

- at the top and outside of a vertical circle.
- at the bottom and inside of a vertical circle.

	Top/outside (N)	Bottom/inside (N)
A	Less than 100	Greater than 100
B	Greater than 100	100
C	Greater than 100	Less than 100
D	100	Greater than 100

EXAM-STYLE QUESTIONS

This lesson

For all questions assume $g = 9.8\text{ m s}^{-2}$.

Question 5 (4 MARKS)

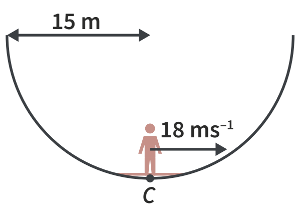
A car drives over a hill in the road which can be modelled as a circle with a radius of 5.2 m at the top.

a Draw a diagram and include arrows to show the forces on the car when it is at the top of the hill. The magnitude of the forces is not required. (2 MARKS)

b Calculate the speed that the car must be travelling at the peak of the hill in order to experience zero normal force. (2 MARKS)

Question 6 (3 MARKS)

A 60 kg skier skis down a bowl-shaped ramp which has a radius of 15 m. At the ramp's lowest point, *C*, she is travelling at 18 m s^{-1}.



a Copy the diagram and draw an arrow to show the direction of the net force on the skier at point *C*. The magnitude of the force is not required. (1 MARK)

b Calculate the magnitude of the force exerted by the bowl on the skier at the point *C*. (2 MARKS)

Adapted from 2015 VCAA Exam Section A Q3

Question 7 (6 MARKS)

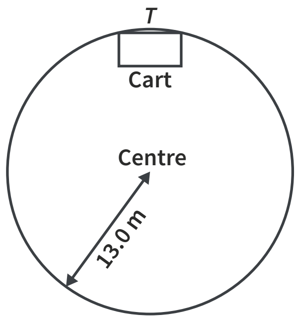
A motorcyclist of 80.0 kg is travelling around a loop-the-loop. At the top of the loop he is travelling at 12.0 m s^{-1} and reports feeling zero gravity.

a Calculate the radius of the loop which causes the motorcyclist to report feeling 'zero gravity'. (2 MARKS)

b Is the motorcyclist experiencing a force due to gravity at the top of the loop? Explain the motorcyclist's experience. (2 MARKS)

c The motorcyclist goes around a second loop of radius 12.0 m travelling at 16.0 m s^{-1}. Calculate the magnitude of the normal force applied at the top of the loop on the motorcyclist. (2 MARKS)

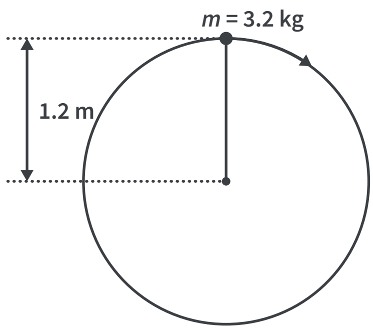
Question 8 (3 MARKS)



A roller coaster designer wants to know whether a cart travelling at 9.0 m s^{-1} at point *T* is safe to ride. Considering the cart has a mass of 320 kg and the loop has a radius of 13.0 m, will the cart stay on the track if it is not supported by an upwards force?

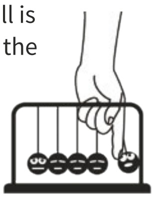
Question 9 (5 MARKS)

A ball of mass 3.2 kg is being spun in a perfect vertical circle at the end of a string. The string has a length of 1.2 m.



a Calculate the minimum speed the ball must have at the top of its arc so that the string remains taut. (2 MARKS)

b The string will break at a tension of 150 N. If the ball is travelling at 7.3 m s^{-1} at the bottom of the arc, will the string break? (3 MARKS)



Previous lessons

Question 10 (3 MARKS)

Blocks A, B, and C have masses of 10, 20, and 5.0 kg respectively. They are pushed along a frictionless surface and stay in contact while moving. Calculate the magnitude of the force $F_{on\ C\ by\ B}$.

Question 11 (2 MARKS)

A ball of mass 0.40 kg is spun horizontally on a frictionless surface and is attached to a string of length 0.75 m with a break strain of 12 N. The speed of the ball is gradually increased. What is the speed of the ball when the string breaks?

Key science skills

Question 12 (3 MARKS)

Xanthe and Bryn are conducting an experiment where they gradually increase the radius (r) of a vertically looped track and record the minimum speed (v) required for a cart to complete the loop.

a They choose to graph the variables v^2 and r. Identify which axis (vertical or horizontal) should be used for each variable. Justify your answer. (2 MARKS)

b If the data is accurate and recorded in SI units, which of the following values will be closest to the magnitude of the gradient? (1 MARK)

- **A** 0.10
- **B** 3.1
- **C** 4.9
- **D** 9.8

2G PROJECTILE MOTION

Studying projectile motion allows physicists to predict the motion of objects that are thrown, launched, or dropped – from bullets to cricket balls. We do this by separating the vertical and horizontal parts of an object's motion.

2A Kinematics recap	2B Forces recap	2C Inclined planes and connected bodies	2D Basic circular motion	2E Banked circular motion	2F Vertical circular motion	2G Projectile motion

Study design key knowledge dot point

- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance

Key knowledge units

Vertical motion of projectiles	3.3.5.2
Horizontal motion of projectiles	3.3.5.3
Linking vertical and horizontal motion of projectiles	3.3.5.4
Effect of air resistance on projectiles	3.3.5.5

Formulas for this lesson

Previous lessons		**New formulas**
2A	* $v = u + at$	$v_x = v\cos(\theta)$
2A	* $s = ut + \frac{1}{2}at^2$	$v_y = v\sin(\theta)$
2A	* $s = vt - \frac{1}{2}at^2$	$v^2 = v_x{}^2 + v_y{}^2$
2A	* $v^2 = u^2 + 2as$	
2A	* $s = \frac{1}{2}(v + u)t$	
2A	* $v = \frac{\Delta s}{\Delta t}$	

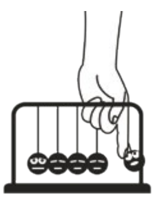
(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

air resistance the force of air particles resisting the motion of objects through the air. Also known as the drag force in air

projectile an object that has been launched or dropped but does not experience a propulsion/thrust force during its motion

range the maximum horizontal distance a projectile travels



Vertical motion of projectiles 3.3.5.2

OVERVIEW

In order to solve projectile motion questions, we separate the vertical and horizontal components and use the equations of constant acceleration. We will begin with modelling vertical motion.

THEORY DETAILS

In VCE Physics we will ignore air resistance for any calculations involving projectile motion. The vertical motion of a projectile without air resistance has a **constant acceleration of 9.8 m s^{-2} downwards** due to the force of gravity acting upon it. This means the vertical motion follows the **constant acceleration equations** from lesson 2A.

We give the initial vertical velocity the symbol u_y and the current/final vertical velocity v_y. It is conventional to take up as positive and down, the direction of acceleration due to gravity, as negative. **At the top of a projectile's motion, its vertical velocity is zero.**

It is important to remember that the displacement, s, is a measure of the change in position between two points of motion. In the context of the vertical motion of a projectile, this means that s measures the **change** in the vertical position (or change in height). It does not measure the total distance travelled (see Figure 1).

When answering these questions we can use a system to find the constant acceleration equation that applies to our situation. We first identify the three variables we know, and the one we need to find. The equation that contains them all is the one we need to use to get to our answer (Figure 2).

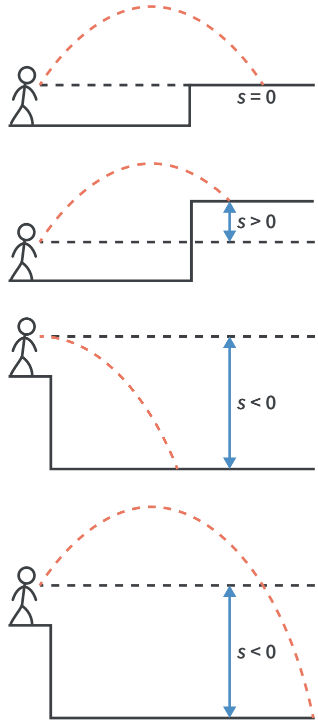


Figure 1 Vertical displacement measures the change in the vertical position of the projectile. If we take upwards as positive, then any motion which results in the projectile finishing at a lower position than it started will have a negative vertical displacement.

	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 2 Two examples of how to find the equations to use in your responses

Upwards initial vertical velocity

Without air resistance, any two projectiles with the same initial vertical velocity will reach the same height at the same time regardless of their mass and horizontal velocity (see Figure 3).

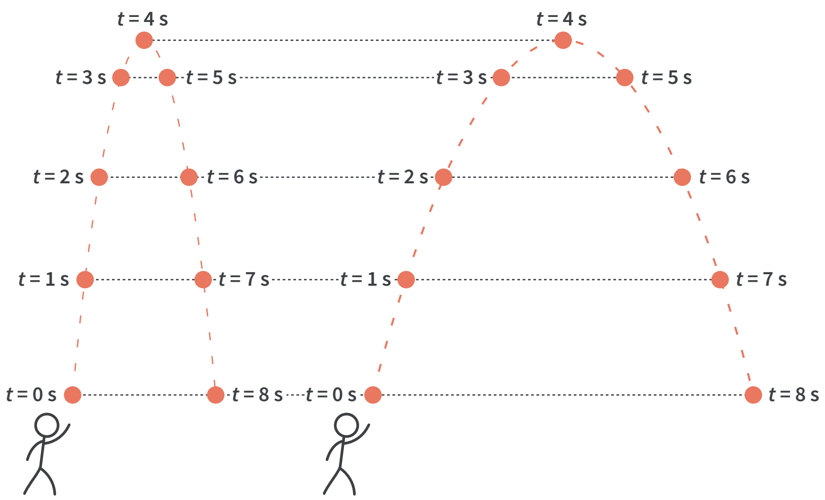


Figure 3 Two balls are thrown with the same initial vertical velocities. The two balls have the same vertical position at each point in time.

The vertical velocity at any time is equal in magnitude but opposite in direction to the velocity at the point on the other side of the arc (see Figure 4). For example, if a ball is thrown upwards out of the girl's hands at 10 m s^{-1}, it will return moving downwards back into her hands at 10 m s^{-1}.

From the symmetry shown in Figures 3 and 4, we can make the following conclusions for a projectile that lands at the same height as that from which it was launched:

- The magnitude of the vertical component of the launch velocity is equal to the magnitude of the vertical component of the landing velocity $(u_{launch} = -v_{landing})$.
- The time taken to return to the starting height is twice the time taken to reach the maximum height $\left(t_{final} = 2 \times t_{max\ height}\right)$.

Note that this symmetry is a special case and occurs only when the projectile lands at the same height at which it is launched.

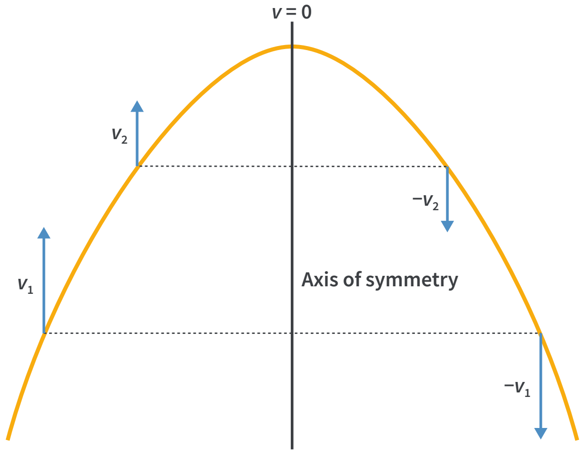


Figure 4 Vertical velocity is equal in magnitude and opposite in direction over the axis of symmetry, and zero at the maximum height.

1 Worked example

A ball is launched off the ground at an angle and has an initial vertical velocity of 19 m s^{-1} upwards. Ignore the effects of air resistance.

a **How long does the ball take to get to the maximum height?**

b **Find the maximum height the ball reaches.**

c **How long is the ball in the air?**

a $a = -9.8$ m s^{-2}, $u = 19$ m s^{-1}, and at maximum height the ball stops ascending so $v = 0$. Solve for t:

$s \quad u \quad v \quad a \quad t$

$\boxed{v = u + at}$

$s = ut + \frac{1}{2}at^2$

$s = vt - \frac{1}{2}at^2$

$v^2 = u^2 + 2as$

$s = \frac{1}{2}(v + u)t$

$v = u + at \quad \therefore 0 = 19 + (-9.8) \times t$

$t = 1.94 = 1.9$ s

b $a = -9.8$ m s^{-2}, $u = 19$ m s^{-1}, $v = 0$. Solve for s:

$s \quad u \quad v \quad a \quad t$

$v = u + at$

$s = ut + \frac{1}{2}at^2$

$s = vt - \frac{1}{2}at^2$

$\boxed{v^2 = u^2 + 2as}$

$s = \frac{1}{2}(v + u)t$

$v^2 = u^2 + 2as \quad \therefore 0 = 19^2 + 2 \times (-9.8) \times s$

$s = 18$ m

c The ball takes twice as long to return to the ground as it takes to reach a maximum height.

$t = 2 \times 1.94 = 3.88 = 3.9$ s

Zero initial vertical velocity

When the initial vertical velocity is zero, the projectile must start at its maximum height as it always accelerates downwards. We cannot use symmetry here as there is no upwards path to compare with, but this motion can be analysed using the same equations of constant acceleration.

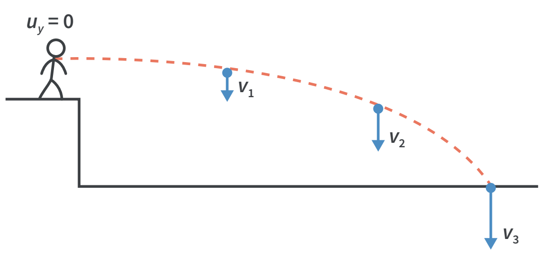
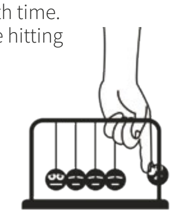


Figure 5 The magnitude of the vertical velocity starts from zero and increases (always pointing downwards) with time. Note that v_3 represents the vertical speed just before hitting the ground.



2 **Worked example**

A rock is thrown horizontally off a cliff and it takes 6.0 seconds to hit the water. Take upwards as positive. Ignore the effects of air resistance.

a **Find the vertical velocity of the rock before it hits the water.**

b **Find the height from which the rock was thrown.**

a $a = -9.8$ m s^{-2}, $u = 0$ m s^{-1} since the rock is thrown horizontally, and $t = 6.0$ s. Solve for v:

$v = u + at = 0 + (-9.8) \times 6.0 = -58.8 = -59$ m s^{-1}

b Use the same known values to solve for s:

$s = ut + \frac{1}{2}at^2 = 0 \times 6.0 + \frac{1}{2} \times (-9.8) \times 6.0^2 = -176.4 = -1.8 \times 10^2$ m

This value is the displacement of the rock from the cliff to the water (which is downwards). This means the height is 1.8×10^2 m.

Horizontal motion of projectiles 3.3.5.3

OVERVIEW

The horizontal motion of a projectile is independent from its vertical motion. When we ignore air resistance, there is no force acting upon a projectile in the horizontal direction so we model projectiles as moving with a constant horizontal component of velocity.

THEORY DETAILS

Just as we can exclude horizontal motion and forces when analysing the vertical motion of a projectile, we exclude vertical motion and forces when analysing horizontal motion. There are no forces acting upon the projectile in the horizontal direction which means the horizontal velocity is **constant** (see Figure 6). This means there is no need to distinguish between initial and final velocities in the horizontal direction ($u_x = v_x$).

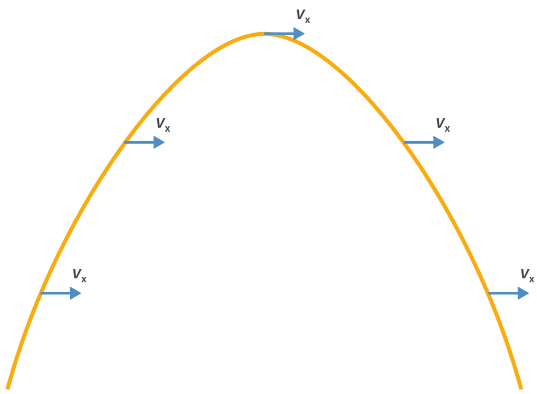


Figure 6 The horizontal velocity is the same at all points.

Because velocity is constant in horizontal projectile motion, we use the equation $v = \frac{\Delta s}{\Delta t}$ to relate velocity, displacement and time. We can write this equation as $v_x = \frac{s_x}{t}$ by choosing to define the initial displacement and time as zero. This allows for a more consistent use of notation between the horizontal and vertical motion.

3 **Worked example**

A football player is attempting to kick a goal from a distance 60 m. Her kick has an initial horizontal velocity of 13 m s^{-1}. Ignore the effects of air resistance.

a **What is the ball's horizontal velocity at its maximum height?**

b **If the ball takes 5.0 s to land and is on target, determine whether or not it reaches the goals.**

a As the ball's horizontal velocity never changes, it's horizontal velocity will be 13 m s^{-1} at its maximum height.

b Use the relationship between velocity, displacement, and time for a constant velocity.

$v_x = \frac{s_x}{t} \therefore 13 = \frac{s_x}{5.0}$

$s_x = 65$ m

The ball travels 65 m, so it will reach the goals.

Linking vertical and horizontal motion of projectiles 3.3.5.4

OVERVIEW

The parabolic arc of a projectile's motion relies upon its vertical acceleration due to gravity and its constant horizontal velocity. Time is the only value which is common to both directions of motion.

THEORY DETAILS

When solving a problem for projectile motion we will usually resolve (separate) the velocity, v, into its horizontal (v_x) and vertical (v_y) components so that we can analyse the horizontal and vertical motion independently. We do this using trigonometry.

$$v_x = v\cos(\theta)$$

v_x = horizontal component of velocity (m s^{-1}), v = velocity magnitude (m s^{-1}), θ = angle of velocity measured from the horizontal (°)

$$v_y = v\sin(\theta)$$

v_y = vertical component of velocity (m s^{-1}), v = velocity magnitude (m s^{-1}), θ = angle of velocity measured from the horizontal (°)

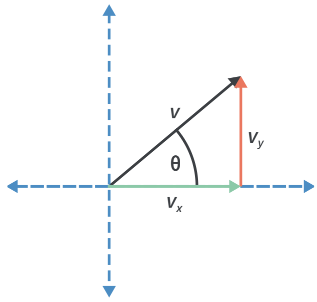


Figure 7 A velocity vector (v) pointing at an angle θ above the horizontal is resolved into its horizontal (v_x) and vertical (v_y) parts.

As with any vector in two dimensions, the magnitude of the velocity can be related to its components using Pythagoras' theorem.

$$v^2 = v_x^{\ 2} + v_y^{\ 2}$$

v = velocity magnitude (m s^{-1}), v_x = horizontal component of velocity (m s^{-1}), v_y = vertical component of velocity (m s^{-1})

Time is the only common value between the vertical and horizontal components of projectile motion. This means we will often calculate the time for the projectile motion using data in one direction (either vertical or horizontal motion) and then use this time to calculate values in the other direction of motion.

The following 'problem solving process' can be used for projectile motion questions which involve both the vertical and horizontal components of motion.

Problem solving process

1. Identify which direction (vertical or horizontal) defines the end of the projectile motion.
2. Use the appropriate equations for the direction identified in step 1 to calculate the time for the projectile motion.
3. Use the time from step 2 to calculate the unknown value(s) required in the other direction.

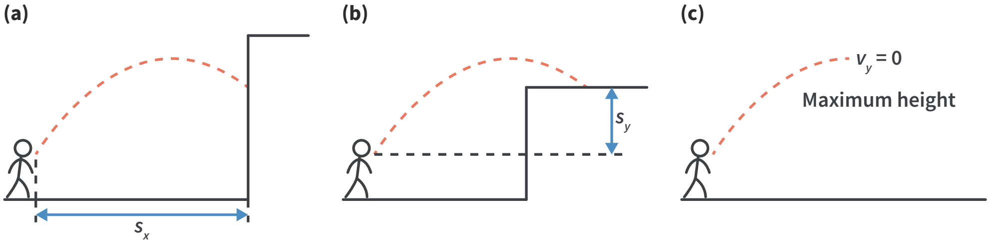
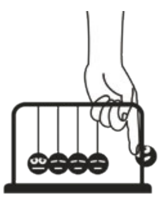


Figure 8 Projectile motion which has an end defined by **(a)** its horizontal position, **(b)** its vertical position, and **(c)** its vertical velocity.



4 Worked example

A golfer hits a ball with a velocity of 20 m s^{-1} at an angle of 30° above the horizontal. The golf course is flat (the ground has the same height at all positions). Ignore the effects of air resistance.

a **Calculate the range of the ball.**

b **Calculate the height of the ball when it has travelled a horizontal distance of 15 metres.**

c **Calculate the ball's velocity when it has travelled a horizontal distance of 25 metres.**

In this question, we will take upwards as positive. All calculations will use unrounded values.

It is useful to resolve the initial velocity vector into its components at the beginning:

Horizontal velocity: $u_x = v_x = v\cos(\theta) = 20 \times \cos(30°) = 17.32$ m s^{-1}

Vertical velocity: $u_y = u\sin(\theta) = 20 \times \sin(30°) = 10$ m s^{-1}

We will follow the previous 'problem solving process' for each part of this question.

a The end of the projectile motion is defined by its vertical motion: when $s_y = 0$ m (the ball hits the ground).

Vertical motion: $a = -9.8$ m s^{-2}, $s_y = 0$ m, $u_y = 10$ m s^{-1}. Solve for t.

$s_y = u_y t + \frac{1}{2}at^2 \;\therefore\; 0 = 10 \times t + \frac{1}{2} \times (-9.8) \times t^2$

$t = 2.04$ s.

$t = 0$ is also a solution to the equation but it describes the time when the ball leaves the ground, rather than when it lands.

Horizontal motion: $v_x = 17.32$ m s^{-1}, $t = 2.04$ s. Solve for s_x.

$v_x = \frac{s_x}{t} \;\therefore\; 17.32 = \frac{s_x}{2.04}$

$s_x = 35$ m. The range is 35 m.

b The end of the projectile motion is defined by its horizontal motion: when $s_x = 15$ m.

Horizontal motion: $v_x = 17.32$ m s^{-1}, $s_x = 15$ m. Solve for t.

$v_x = \frac{s_x}{t} \;\therefore\; 17.32 = \frac{15}{t}$

$t = 0.866$ s

Vertical motion: $a = -9.8$ m s^{-2}, $u_y = 10$ m s^{-1}, $t = 0.866$ s. Solve for s.

$s_y = u_y t + \frac{1}{2}at^2 \;\therefore\; s_y = 10 \times 0.866 + \frac{1}{2} \times (-9.8) \times 0.866^2$

$s_y = 4.99 = 5.0$ m. The ball is 5.0 m above the ground when it has travelled a horizontal distance of 15 m.

c To provide the velocity of the ball, we need to provide both the magnitude and the direction (angle). This means we need both the vertical and horizontal components of the velocity.

The end of the projectile motion is defined by its horizontal motion: when $s_x = 25$ m.

Horizontal motion: $v_x = 17.32$ m s^{-1}, $s_x = 25$ m. Solve for t.

$v_x = \frac{s_x}{t} \;\therefore\; 17.32 = \frac{25}{t}$

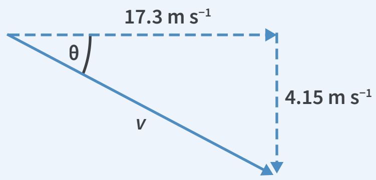
$t = 1.443$ s

Vertical motion: $a = -9.8$ m s^{-2}, $u_y = 10$ m s^{-1}, $t = 1.443$ s. Solve for v_y.

$v_y = u_y + at \;\therefore\; v_y = 10 + (-9.8) \times 1.443$

$v_y = -4.15$ m s^{-1}

The diagram represents the velocity vector at this time (not to scale).



Calculate the magnitude of the velocity.

$v = \sqrt{v_x^2 + v_y^2} = \sqrt{17.3^2 + (-4.15)^2} = 17.8 = 18$ m s^{-1}

Calculate the direction (angle) of the velocity.

$\tan(\theta) = \frac{4.15}{17.3}$

$\theta = 13°$

The velocity of the projectile is 18 m s^{-1} at an angle of 13° below the horizontal.

Effect of air resistance on projectiles 3.3.5.5

OVERVIEW

Air resistance is a force applied by the air on a projectile, opposing its motion through the air. It reduces the distance a projectile can travel in both the vertical and horizontal directions.

THEORY DETAILS

Air resistance is a drag force. The force acts in the opposite direction to the motion of the object and its magnitude (size) increases as the velocity of the object increases. It acts to slow the object in both the vertical and horizontal directions, leading to a reduced maximum height and range (see Figure 9).

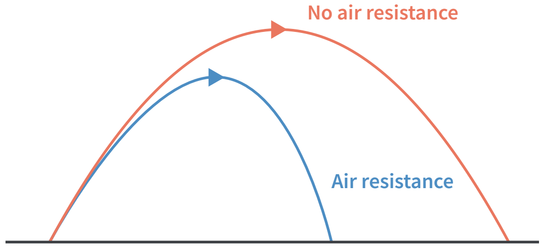


Figure 9 Comparison of projectile trajectories with and without the effects of air resistance

Theory summary

- We separate the vertical and horizontal parts of a projectile's motion.
- Vertical motion:
  - There is a constant acceleration downwards, due to gravity.
  - Use the five uniform acceleration equations to describe the motion.
  - At maximum height, the vertical velocity is zero.
- Horizontal motion:
  - The horizontal velocity is constant.
  - Use $v_x = \frac{s_x}{t}$ to describe the motion.
- We use time to relate the horizontal motion to the vertical motion.
- Air resistance resists motion in both directions and causes a reduced range, slower speeds, and an asymmetrical trajectory.

KEEN TO INVESTIGATE?

oPhysics 'Projectile Motion' simulation
https://ophysics.com/k8.html

PhET 'Projectile Motion' simulation
https://phet.colorado.edu/en/simulation/projectile-motion

YouTube video: Harvard Natural Sciences Lecture Demonstrations – Shoot-n-Drop
https://youtu.be/zMF4CD7i3hg

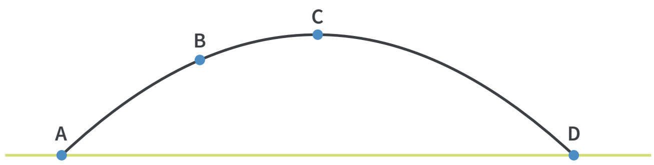
2G Questions

THEORY REVIEW QUESTIONS

Unless otherwise stated, ignore the effects of air resistance in the following questions.

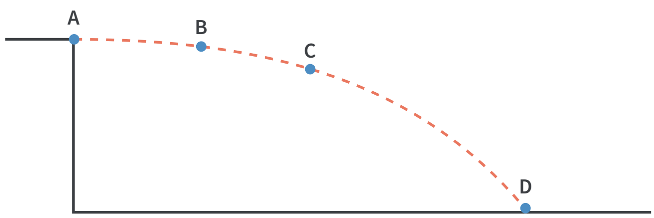
Question 1

At which point is the vertical velocity zero?



Question 2

At which point is the horizontal velocity equal to the total velocity?



Question 3

A stone is thrown at an angle of 30° and lands 40 m away. Its horizontal velocity when thrown was 10 m s^{-1}. What is its horizontal velocity just before it lands?

A 10 m s^{-1}

B 5.0 m s^{-1}

C 8.7 m s^{-1}

D −10 m s^{-1}

Question 4

By vector addition, determine which is the magnitude of the velocity vector *v* considering its horizontal and vertical components are 3.00 m s^{-1} and 4.00 m s^{-1}, respectively.

A 1.00 m s^{-1}

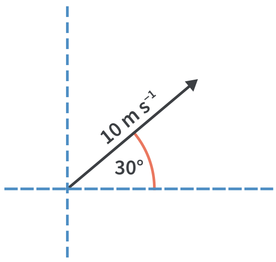
B 5.00 m s^{-1}

C 7.00 m s^{-1}

D It cannot be calculated with the information given.

Question 5

A ball is thrown into the air at 30° with an initial velocity of 10 m s^{-1} as per the vector diagram.



Which of the following correctly represents the horizontal and vertical components of the ball's initial velocity vector?

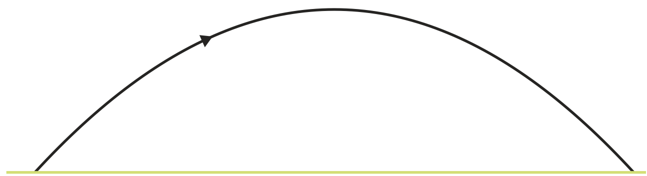
	Horizontal velocity (m s^{-1})	Vertical velocity (m s^{-1})
A	$10 \times \sin(30°)$	$10 \times \tan(30°)$
B	$10 \times \tan(30°)$	$10 \times \sin(30°)$
C	$10 \times \sin(30°)$	$10 \times \cos(30°)$
D	$10 \times \cos(30°)$	$10 \times \sin(30°)$

EXAM-STYLE QUESTIONS

This lesson

Question 6 (2 MARKS)

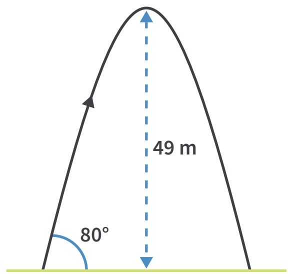
Neo is playing around with the settings in his Matrix simulator which is powerful enough to simulate any and all physics. He turns the air resistance off and kicks a football as hard as possible, represented by the solid line. He then tries again with air resistance back on.



Copy the diagram and draw a possible path of the football, with air resistance applied, using a dotted line.

Question 7 (5 MARKS)

Jeremy is playing around with an air rocket. He launches the rocket at an angle of 80° and records a maximum height of 49 m.



a Calculate the initial vertical velocity of the rocket. (2 MARKS)

b Calculate the rocket's range. (3 MARKS)

Adapted from 2012 VCAA Exam 1 Section A AoS 1 Q6

Question 8 (7 MARKS)

A cricket ball is hit with a velocity of 32.0 m s^{-1} at an angle of 50.0° above the horizontal. Assume the ball is hit at ground level and the cricket pitch is perfectly flat.

a What is the maximum height the ball reaches? (2 MARKS)

b The ball hits the wall of a stadium which is a horizontal distance of 90 m away from where it was hit. At what height does the ball hit the wall? (3 MARKS)

c How far would the ball have travelled if it was not blocked by the stadium wall and landed at the same height from which it was hit? (2 MARKS)

Question 9 (6 MARKS)

A ball is launched horizontally from a table of height 1.2 m with a speed of 7.00 m s^{-1}.

a How far does the ball travel horizontally from the edge of the table before hitting the ground? (3 MARKS)

b Calculate the magnitude and direction of the velocity of the ball just before it hits the ground. (3 MARKS)

Question 10 (3 MARKS)

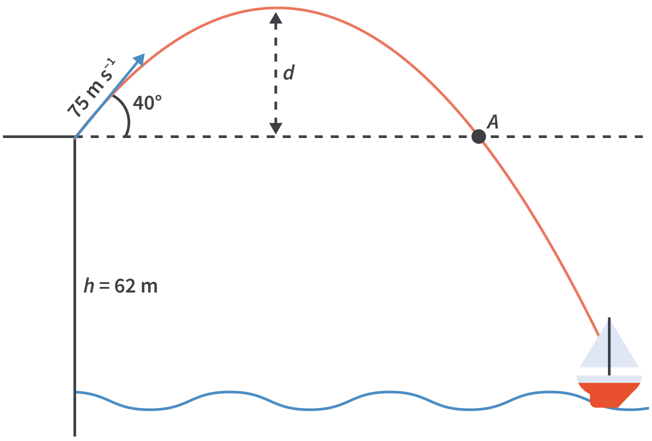
Madeline throws a stone horizontally from the top of a cliff. It hits the ground 80 m from the base of the cliff 5.0 seconds later.

a Calculate the height of the cliff. (2 MARKS)

b Madeline is wondering if she can hit a can placed 280 m away from the base of the cliff. What magnitude of horizontal velocity would she need to hit the can? (1 MARK)

Question 11 (8 MARKS)

Isaac tests his catapult's effectiveness against enemy ships by launching a 20.0 kg stone with a speed of 75 m s^{-1} at an angle of 40° above the horizontal into the ocean. The stone is launched from the top of a cliff that is 62 m above the water.



a Calculate the maximum height, *d*, above the cliff that the stone reaches. (2 MARKS)

b Calculate the horizontal distance to point *A*, which is at the same height as the cliff. (3 MARKS)

c The enemy's boats can withstand stones with speeds of up to 70.0 m s^{-1} without sinking. Find the speed of Isaac's stone as it hits the water and determine whether a boat in this position would sink. (3 MARKS)

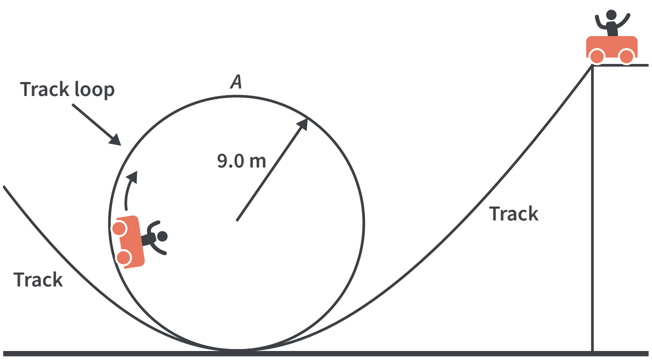
Previous lessons

Question 12 (2 MARKS)

A 1200 kg car rounds a corner on a flat road with a radius of 20 m and maintains a speed of 40 m s^{-1}. Calculate the magnitude of the net force on the car.

Question 13 (2 MARKS)

A loop is constructed with a radius of 9.0 m. Considering the total mass of a cart and rider is 400 kg, calculate the magnitude of the minimum velocity the cart must be travelling at at point *A* so that it does not fall off the tracks.



Adapted from 2009 VCAA Exam 1 Section A AoS 1 Q12

Key science skills

Question 14 (4 MARKS)

A group of students use a mechanised slingshot to investigate projectile motion. They each take five measurements of the time taken for the projectile to land, which is shown in the table. The true time taken in each case is 12.0 seconds.

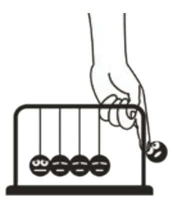
	Achol	Bonnie	Camara	Donald
Time 1 (s)	10.0	12.2	12.3	9.00
Time 2 (s)	10.2	12.0	6.40	15.0
Time 3 (s)	10.4	11.8	11.2	12.0
Time 4 (s)	10.3	11.9	11.4	13.5
Time 5 (s)	10.3	12.2	4.50	10.5
Average (s)	10.2	12.0	9.16	12.0

One of the students can be said to have produced a set of precise but inaccurate results.

a Which student is this? Justify your answer. (2 MARKS)

b Comment on the relative effect of random errors and systematic errors on this student's results. (2 MARKS)

Adapted from 2019 VCAA NHT Exam Section A Q20



CHAPTER 2 QUESTIONS

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

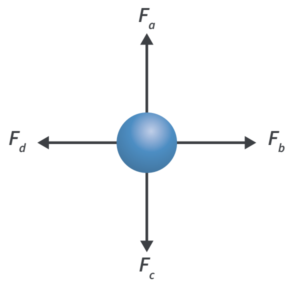
A toy car of mass 1.5 kg is propelled forward by a net force of 3.0 N. What is the magnitude of the acceleration of the toy?

A 0.5 m s^{-2} **B** 4.5 m s^{-2} **C** 2.0 m s^{-2} **D** 1.5 m s^{-2}

Adapted from 2017 VCAA Exam Section A Q7

Question 2

Four different forces act on a body simultaneously. F_a = 18 N, F_b = 34 N, F_c = 14 N and F_d = 26 N. What is the magnitude of the resultant force on the body? Force vectors in the diagram are not drawn to scale.



A 20 N

B 22 N

C 9.6 N

D 8.9 N

Adapted from 2018 VCAA Exam Section A Q5

Question 3

A race track is designed so that when cars go around a corner they do not exert any sideways friction force in order to turn. The radius of the corner is 55 m and cars move around it at 60 km h^{-1}. What is the bank angle of the corner?

A 62° **B** 27° **C** 10° **D** 6.4°

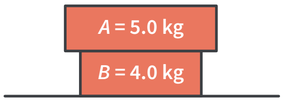
Question 4

In a roller coaster loop the loop, engineers have designed the track so that passengers will experience zero normal force at the top of the loop. The loop has a radius of 7.0 m and the combined mass of the cart and passengers is 450 kg. What speed must the cart be going at the top of the loop to achieve this?

A 8.3 m s^{-1} **B** 42 m s^{-1} **C** 67 m s^{-1} **D** 11 m s^{-1}

Question 5

Whilst making a geometric sculpture, a person places brick *A* of 5.0 kg on top of brick *B* of 4.0 kg as per the diagram. What is the magnitude and direction of $F_{\text{on } A \text{ by } B}$?



A 49 N downwards

B 39 N downwards

C 49 N upwards

D 39 N upwards

SECTION B

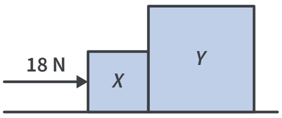
In questions where more than one mark is available, appropriate working must be shown.

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

Question 6 (2 MARKS)

An 18 N force is applied to block *X* (of mass 2.0 kg) which is in contact with block *Y* (of mass 4.0 kg) sitting on a smooth, frictionless surface.

Calculate the force on block *Y* by block *X*.



Adapted from 2018 VCAA Exam Section B Q8

Question 7 (4 MARKS)

A 1600 kg car is pulling a trailer that has a mass of 600 kg. The trailer is connected to the car through a metal coupling. The car accelerates from rest at a rate of 0.50 m s^{-2}.

a Calculate the time it takes for the car to have a speed of 10 m s^{-1}. (2 MARKS)

b The trailer provides a constant resistance force of 1000 N. Calculate the tension in the metal coupling between the car and the trailer. (2 MARKS)

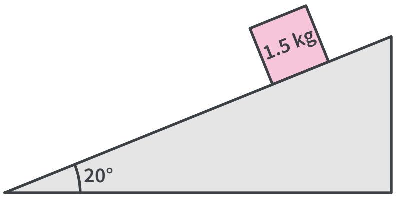
Adapted from 2016 VCAA Exam Section A Q1

Question 8 (4 MARKS)

A 1.5 kg block is placed on a ramp at an angle of 20° to the horizontal. A constant friction force acts on the block as it starts from rest and slides down the ramp. The ramp is 1.5 m long and the block takes 5.0 s to slide to the bottom of the ramp.

a Calculate the acceleration of the block. (2 MARKS)

b Hence calculate the magnitude of the frictional force acting on the block. (2 MARKS)



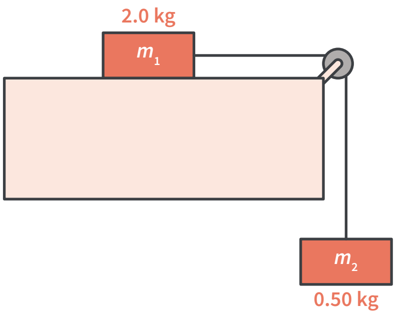
Adapted from 2013 VCAA Exam Section A Q1

Question 9 (3 MARKS)

A physics student is investigating the concept of acceleration by connecting a mass, m_1, of 2.0 kg, and m_2, of 0.50 kg with a string and letting the second mass hang over the edge of the table. Ignore the mass of the string and any frictional forces.

a Calculate the acceleration of m_1. (2 MARKS)

b Calculate the tension in the string as the mass is falling. (1 MARK)



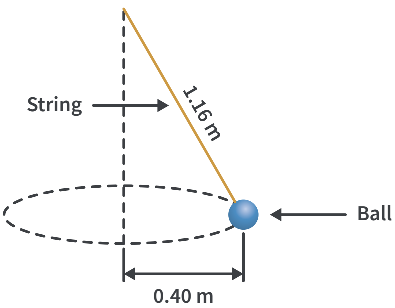
Adapted from 2013 VCAA Exam Section A Q2

Question 10 (5 MARKS)

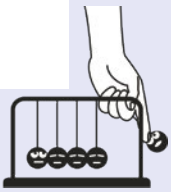
A child is swinging a ball attached to a string in a horizontal circle during break time in school. Being an aspiring physicist, the child decides to take some measurements. The length of the string is 1.16 m and the ball, which has a mass of 0.50 kg, is moving in a circle of radius 0.40 m at 1.2 m s^{-1}.

a Draw a diagram showing all the forces acting on the ball. Draw the net force as a dashed line labelled F_{net}. (2 MARKS)

b Calculate the tension in the string. (3 MARKS)

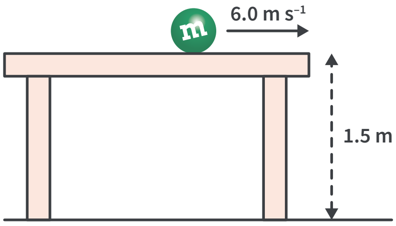


Adapted from 2016 VCAA Exam Section A Q2



Question 11 (6 MARKS)

A giant M&M is rolled off a bench that is 1.5 m above the ground. It has a speed of 6.0 m s^{-1} when it leaves the bench. If the M&M hits the ground at a speed greater than 7.0 m s^{-1} it will shatter. Ignore all friction and resistance forces.



a Calculate the horizontal distance that the M&M travels before it hits the ground. (3 MARKS)

b Does the M&M tragically break when it hits the ground? (3 MARKS)

Question 12 (4 MARKS)

Lance is riding his bike around a circular banked track of radius 45 m to legally and ethically win La Tour de Straya. Lance and his bike have a combined mass of 85 kg and travel at 14 m s^{-1}.

a What is the net force acting on Lance and in which direction does it act? (2 MARKS)

b Calculate the correct angle of bank for there to be no sideways frictional force applied by the track on the wheels. (2 MARKS)

Adapted from 2017 VCAA Exam Section B Q7

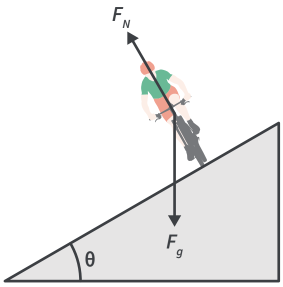
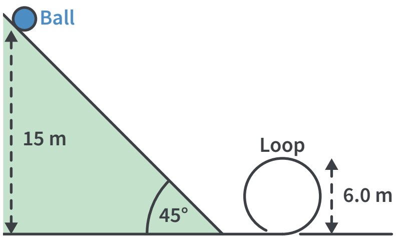


Image: Michal Sanca/Shutterstock.com

Question 13 (8 MARKS)

A ball of mass 1.50 kg is placed at the top of a hill with a 6.0 metre tall loop at the bottom. The hill is 15 metres tall and is inclined at an angle of 45°. All surfaces are frictionless.



a Calculate the acceleration of the ball down the hill. (2 MARKS)

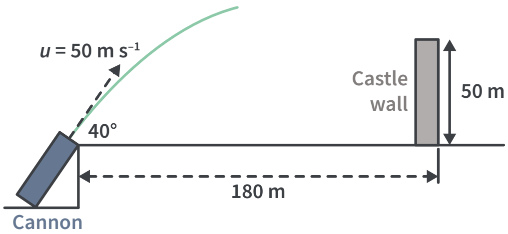
b Calculate the speed of the ball at the bottom of the hill. (3 MARKS)

c Calculate the minimum speed the ball must have at the top of the loop in order to stay in contact with the loop. (1 MARK)

d Suppose the speed of the ball at the top of the loop is 13 m s^{-1}. Calculate the value of the normal force, F_N, acting on the ball by the track at this point. (2 MARKS)

Question 14 (9 MARKS)

Hundreds of years ago, a great wager occurred where a king bet a poor village man that he could not create a cannon powerful enough to launch a stone over his castle's 50 m high walls. Luckily, the poor village man has a keen understanding of projectile motion. He knows that his cannon can launch the stone at 50 m s^{-1} at an angle of 40° above the horizontal, and that his cannon is 180 metres from the king's wall.



a Calculate the maximum height that the man's stone will reach. (2 MARKS)

b Calculate how long it takes for the stone to travel the 180 m to the wall. (2 MARKS)

c Calculate the speed of the stone projectile when it has travelled the distance to the wall. (2 MARKS)

d Should the village man take up the king's wager? Justify your answer with calculations. (3 MARKS)

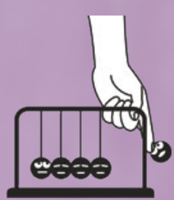
UNIT 3 AOS 3, CHAPTER 3

Momentum and energy

03

Key knowledge

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$
- investigate and apply theoretically and practically the concept of work done by a constant force using:
  - work done = constant force × distance moved in direction of net force
  - work done = area under force-distance graph
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass



3A MOMENTUM AND IMPULSE

When a car applies its brakes or a truck crashes into a wall, different forces act on the object to change its velocity. How do these forces relate to safety equipment such as airbags? This lesson will explore the basics of momentum and impulse.

3A Momentum and impulse	3B Kinetic energy, work and power	3C Elastic and inelastic collisions	3D Gravitational potential energy	3E Strain potential energy	3F Vertical spring-mass systems

Study design key knowledge dot points

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$

Key knowledge units

Momentum	3.3.6.1
Impulse	3.3.13.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $p = mv$
	$p_i = p_f$
	* $I = F\Delta t$
	$I = \Delta p = m\Delta v$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

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 quantity)

isolated system a collection of interacting objects for which there is no external exchange of mass and energy

momentum a quantity for a body in motion which is equal to the mass of the body multiplied by its velocity (vector quantity)

Momentum 3.3.6.1

OVERVIEW

Momentum is a vector quantity measured in kg m s^{-1} or N s which is conserved in an isolated system so that the momentum before a collision will be equal to the momentum after the collision, $p_i = p_f$.

THEORY DETAILS

The momentum of an object is equal to the mass of the object multiplied by its velocity. The direction of momentum is the same as the direction of the velocity.

$p = mv$

p = momentum (kg m s^{-1} or N s), m = mass (kg), v = velocity (m s^{-1})

A body that has a greater momentum will require more force and/or more time to stop, which is why a truck takes longer to stop than a car moving at the same speed.

1 **Worked example**

A truck of mass 10 tonnes is driving north at 30 m s^{-1}. What is the momentum of the truck?

1 tonne = 10^3 kg

$p = mv = 10 \times 10^3 \times 30 = 3.0 \times 10^5$ kg m s^{-1} or N s

The momentum of the truck is 3.0×10^5 kg m s^{-1} or N s to the north.

Conservation of momentum

The law of conservation of momentum states that any interaction or collision between two or more bodies in an isolated system does not change the total momentum of the system. Hence the initial momentum, p_i, will be equal to the final momentum, p_f.

In VCE Physics, all calculation questions involving momentum will assume an isolated system where momentum is conserved.

$p_i = p_f$

p_i = initial momentum (kg m s^{-1} or N s), p_f = final momentum (kg m s^{-1} or N s)

2 **Worked example**

A toy truck of mass 200 g rolls along the ground at a constant speed of 2.0 m s^{-1} when a person places a coin onto the truck. The truck and coin have a combined mass of 250 g. Ignore the effects of friction.

a **Calculate the magnitude of the total momentum of the system before the coin is placed on the toy truck.**

b **What is the total momentum after the coin is placed on the toy truck?**

c **Calculate the speed of the truck and coin after the event.**

a The initial momentum of the coin in the horizontal direction is zero. Hence, the initial momentum of the system is equal to the momentum of the truck before the coin is placed on it.
$p_i = mv = 0.200 \times 2.0 = 0.40$ kg m s^{-1} or N s

b Use conservation of momentum: $p_i = p_f$
$p_f = 0.40$ kg m s^{-1} or N s

c $p_f = mv \;\therefore 0.40 = 0.250 \times v_2$
$v_2 = 1.6$ m s^{-1}

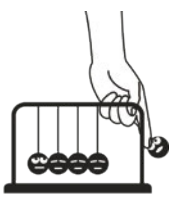
Impulse 3.3.13.1

OVERVIEW

Impulse (I) is a vector quantity that is equal to the change in momentum (Δp) of an object, due to a constant (or average) force (F) that acts over a given time interval (Δt). It is measured in kg m s^{-1} or N s and has the same direction as the change in momentum.

THEORY DETAILS

When a collision occurs, the bodies involved experience a change in momentum due to the forces that act between the bodies. This change in momentum is defined as impulse, I. Hence impulse can have the unit kg m s^{-1}.



$I = \Delta p = m\Delta v$

I = impulse (kg m s^{-1} or N s), Δp = change in momentum (kg m s^{-1} or N s), m = mass (kg), Δv = change in velocity (m s^{-1})

The direction of the impulse is always in the same direction as the change in momentum and velocity.

A force must be involved in any collision between objects, and it is this force which is responsible for the impulse.

Consider Newton's second law, $F = ma$, which can be written as $F = m\frac{\Delta v}{\Delta t}$. By transposing this equation we can write $m\Delta v = F\Delta t$. This leads to the following alternative method for finding impulse.

$I = F\Delta t$

I = impulse (kg m s^{-1} or N s), F = force (N), Δt = change in time (s)

The direction of the impulse is always in the same direction as the force applied.

It is important to note that this equation applies for situations where the force is constant. If the force varies, then the F in this equation is the average force. When calculating impulse with a force and time, it is more common to use newton-seconds (N s) to measure the impulse.

With this understanding of the relationship between impulse and force, we can now interpret the principle of momentum conservation as being equivalent to Newton's third law. Consider the two balls colliding in Figure 1. When ball A collides with ball B, there is a force on ball B by ball A acting to the right and there is a force of equal magnitude on ball A by ball B to the left. Since $I = F\Delta t$ and the change in time is the same, this means ball A gives ball B impulse to the right and ball B gives ball A an equal magnitude of impulse to the left. This means $\Delta p_A = -\Delta p_B$ and so the total momentum of the system is constant.

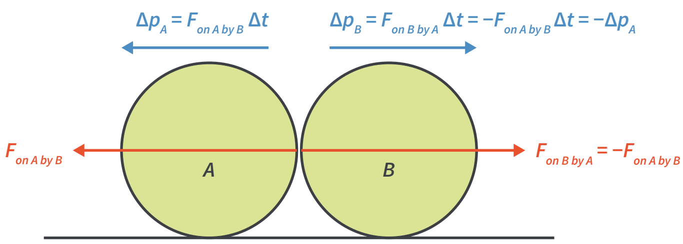


Figure 1 Each ball gives the other impulse with equal magnitude in the opposite direction which means the total momentum is conserved.

3 **Worked example**

A stationary golf ball of mass 45 g is struck by a golf club. The time that the ball is in contact with the club is 5.0 × 10^{-3} s, and the ball has a final velocity of 95 m s^{-1} to the east.

a **Calculate the change in momentum of the golf ball.**

b **Calculate the impulse experienced by the golf ball.**

c **Calculate the impulse experienced by the golf club.**

d **Calculate the average force experienced by the golf ball during its contact with the golf club.**

a $\Delta p_{ball} = m\Delta v = m(v - u) = 45 \times 10^{-3} \times (95 - 0)$

$\Delta p_{ball} = 4.28 = 4.3$ kg m s^{-1} or N s to the east

b $I_{ball} = \Delta p_{ball} = 4.3$ kg m s^{-1} or N s to the east

c $I_{club} = -\Delta p_{ball} = 4.3$ N s or kg m s^{-1} to the west

d $I_{ball} = F_{avg}\Delta t \;\therefore 4.28 = F_{avg} \times 5.0 \times 10^{-3}$

$F_{avg} = 8.6 \times 10^{2}$ N to the east

Impulse in collision safety

Consider the airbag in a car during a crash. If no airbag was present, a passenger's head would impact a solid object and the momentum of their head would reach zero extremely quickly. An airbag will act to extend the impact, and their head's momentum will decrease to zero over a longer duration. Knowing that $I = F\Delta t$, we can rearrange to find $F = \frac{I}{\Delta t}$. The impulse experienced with and without an airbag is equal since the change in momentum is equal. However the airbag increases the time of the collision, Δt, decreasing the force experienced by the head. Increasing the time of a collision is also the principle behind seat belts, helmets, crumple zones, brakes, parachutes, and many other types of safety equipment.

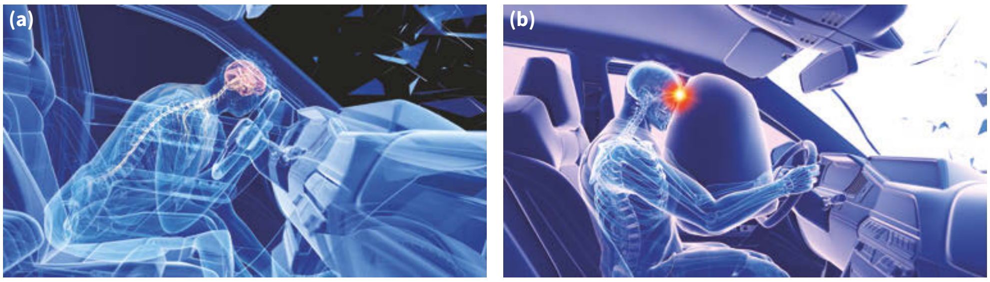


Image: Sebastian Kaulitzki/Shutterstock.com

Image: Sebastian Kaulitzki/Shutterstock.com

Figure 2 **(a)** A car crash without an airbag will result in 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

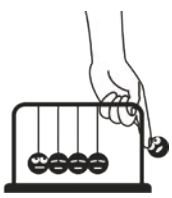
- Momentum is a vector quantity that is a product of a body's velocity and its mass and is measured in kg m s^{-1} or N s.
  - $p = mv$
- The law of conservation of momentum states that the total momentum before a collision will be the same as the total momentum after the collision within an isolated system.
  - $p_i = p_f$
- Impulse is a vector equal to the change in momentum of an object due to a force which acts over a given time.
  - $I = \Delta p = m\Delta v$
  - $I = F\Delta t$
- Impulse can be described in both kg m s^{-1} and N s.
- The direction of impulse is determined by the direction of the change in momentum or the direction of a force causing the impulse.

KEEN TO INVESTIGATE?

YouTube video: Physics Girl – Stacked Ball Drop
https://youtu.be/2UHS883_P60

YouTube video: Professor Dave Explains – Impulse and Momentum
https://youtu.be/E13h1E_Pc00

YouTube video: Veritasium – Bullet Block Experiment
https://youtu.be/vWVZ6APXM4w



3A Questions

THEORY REVIEW QUESTIONS

Question 1

Which option(s) can be used to measure impulse? Select all that apply.

A $m\ s^{-1}$

B N s

C $kg\ m\ s^{-1}$

D N

Question 2

Impulse is best described as

A the change in the momentum of an object.

B the average force experienced by an object.

C the change in the velocity of an object.

D the change in the velocity of an object over a given time.

Question 3

During a collision

A momentum is never conserved.

B momentum is conserved only if the objects after a collision are travelling at the same speed.

C momentum is always conserved if the objects after the collision are travelling in the same direction.

D momentum is always conserved in an isolated system.

Question 4

Two cars with equal mass are travelling down a road at 80 km h^{-1} when the traffic lights in front of them turn red and both cars stop. Car A decelerates very rapidly from 80 km h^{-1} to 0 km h^{-1}, where as Car B slowly decelerates.

Relative to Car B, Car A experiences

A a greater magnitude of impulse.

B a lesser magnitude of impulse.

C the same magnitude of impulse.

D no impulse.

Question 5

After a collision between 2 objects, A and B, object A is found to have a change in momentum of 10 kg m s^{-1} to the left. Which of the options best describes the momentum change of object B after the collision?

A The momentum change of object B will be 10 kg m s^{-1} to the left.

B The momentum change of object B will be 10 kg m s^{-1} to the right.

C The momentum change of object B will be zero.

D There is not enough information to determine the momentum change of object B.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (2 MARKS)

A basketball of mass 0.25 kg is thrown to the right at a speed of 4.0 m s^{-1}. What is the momentum of the ball?

Question 7 (2 MARKS)

A pigeon with a mass of 0.20 kg is in flight with a momentum of magnitude 0.50 kg m s^{-1}. Calculate the speed of the pigeon.

Question 8 (4 MARKS)

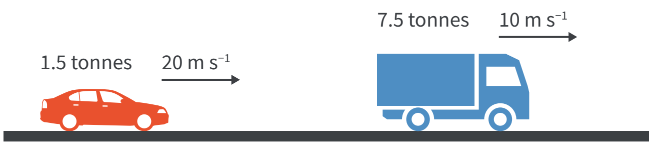
A young adult driving a Subaru WRX approaches an intersection at a speed of 50 m s^{-1}. A car pulls out in front of the WRX which is forced to stop in 8.5 s. The driver and Subaru have a combined mass of 1500 kg.

a Calculate the magnitude of the impulse experienced by the car and driver. (2 MARKS)

b Calculate the magnitude of the average force acting to decelerate the car. (2 MARKS)

Question 9 (9 MARKS)

The included figure shows a car of mass 1.5 tonnes moving to the right at a speed of 20 m s^{-1}, and a truck of mass 7.5 tonnes moving to the right at a speed of 10 m s^{-1}. The two vehicles collide and stick together.



a Calculate the magnitude and direction of the total momentum of the car and truck when they stick together after the collision. (2 MARKS)

b Calculate the speed of the truck and car once they have stuck together after the collision. (2 MARKS)

c State the magnitude, direction, and units of the impulse given to the car by the truck during the collision. (3 MARKS)

d What is the magnitude and direction of the impulse given to the truck by the car during the collision? (2 MARKS)

Adapted from 2013 VCAA Exam Section A Q3

Question 10 (2 MARKS)

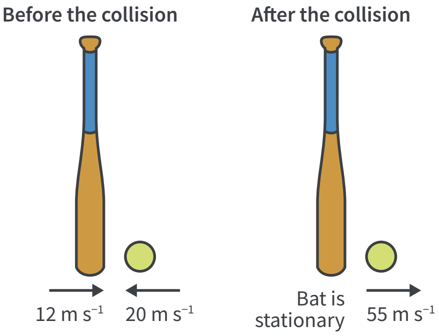
In a game of cricket, a ball of mass 85 g is struck by a bat over a duration of 0.010 s. For a specific hit, the magnitude of the impulse given to the ball is 2.90 N s.

What was the magnitude of average force exerted on the ball by the bat?

Question 11 (5 MARKS)

Students in a physical education class are exploring the breaking point of rubber balls by striking them with a bat whilst they are thrown. The physical education students also possess a good knowledge of momentum and impulse, and decide to calculate one of their failed attempts. They record the included measurements.

Mass of ball	0.40 kg
Mass of bat	2.5 kg
Speed of bat immediately before striking ball	12 m s^{-1} (bat is stationary after collision)
Speed of ball immediately before being struck	20 m s^{-1} (towards bat)
Speed of ball immediately after being struck	55 m s^{-1} (away from bat)
Average force between the ball and bat	1.2×10^3 N



a Calculate the magnitude of the impulse given to the ball by the bat. Include an appropriate unit in your answer. (3 MARKS)

b Calculate the time that the ball is in contact with the bat. (2 MARKS)

Adapted from 2019 NHT VCAA Exam Section B Q7

Previous lessons

Question 12 (3 MARKS)

A clown at the circus is riding on a miniature bike in a circle of radius 8.0 m. The floor of the circus is flat. The clown is able to move at a constant speed of 3.0 m s^{-1}. The clown and their miniature bike have a combined mass of 110 kg.

a What is the magnitude of the net force acting on the clown and the miniature bike? (2 MARKS)

b Copy the included diagram, and add an arrow to show the direction of the net force on the clown and their miniature bike. (1 MARK)

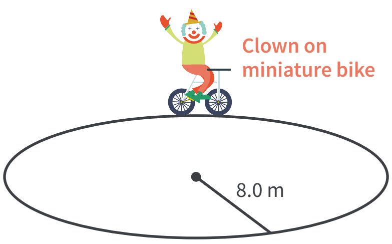
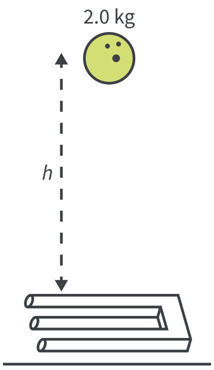


Image: Graphiqa Stock/Shutterstock.com

Adapted from 2009 VCAA Exam 1 Section A AoS 1 Q3-4

Question 13 (4 MARKS)

An angry teenager drops a bowling ball from rest, in order to crush a frustrating optical illusion. The bowling ball falls h metres before contacting the optical illusion. The bowling ball takes 0.50 s to make contact with the optical illusion. Take g = 9.8 m s^{-2}.



a Calculate the distance h in metres. Show your working. (2 MARKS)

b Calculate the speed of the bowling ball as it makes contact with the optical illusion. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q7

Key science skills

Question 14 (8 MARKS)

Students conduct a physics experiment in which they use a toy car moving at a known constant velocity with variable mass, and collide it with another stationary car of known mass. The students use a tape measure and a stopwatch to measure the velocity of the second car. Due to the inaccuracy of this method, the students estimate the uncertainty of the final momentum to be ± 3.0 kg m s^{-1}. They record the following data.

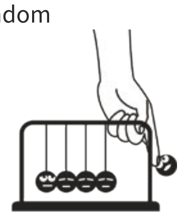
Initial Momentum (kg m s^{-1})	Final Momentum (± 3.0 kg m s^{-1})
9	10
15	13
22	21
26	28
31	29

a On a set of axes: (5 MARKS)

- plot a graph of final momentum versus initial momentum using the data in the table provided
- include appropriate uncertainty bars for the final momentum values
- label each axis correctly
- include an appropriate scale
- Include a line of best fit

b Use the graph from part **a** to determine whether the students' data supports the law of conservation of momentum. Explain your answer. (2 MARKS)

c Suggest a way in which students could reduce random errors in their experiment. (1 MARK)



3B KINETIC ENERGY, WORK AND POWER

This lesson is primarily about the energy associated with motion, which is core to Unit 3 Area of Study 3, and it provides grounding for the concept of energy which is a fundamental tool for all aspects of physics.

3A Momentum and impulse	3B Kinetic energy, work and power	3C Elastic and inelastic collisions	3D Gravitational potential energy	3E Strain potential energy	3F Vertical spring-mass systems

Study design key knowledge dot points

- investigate and apply theoretically and practically the concept of work done by a constant force using:
  - work done = constant force × distance moved in direction of net force
  - work done = area under force-distance graph
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

Key knowledge units

Kinetic energy	3.3.15.1
Work done	3.3.14.1
Power as the rate of change in energy	2.1.15.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $KE = \frac{1}{2}mv^2$
	$W = Fs$
	$P = \frac{\Delta E}{\Delta t}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

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

kinetic energy the energy of an object due to its motion

power the rate of change in energy with respect to time

work the change in energy caused by a force acting on an object in a direction parallel to its motion

Kinetic energy 3.3.15.1

OVERVIEW

Kinetic energy is the energy associated with an object because of its motion. The SI unit for all types of energy is joules (J) and it is a scalar quantity – it does not have an associated direction.

THEORY DETAILS

In classical physics, the kinetic energy of an object is related to its mass and speed by the following formula:

$$KE = \frac{1}{2}mv^2$$

KE = kinetic energy (J), m = mass (kg), v = speed (m s^{-1})

Note that the VCE Physics Study Design uses the abbreviation E_k for kinetic energy. For the purposes of making an obvious distinction between different forms of energy, this book will usually use KE.

The benefit of quantifying kinetic energy will become clear in the next section, which explores the concept of work, and in later lessons in chapter 3 when we introduce other types of energy which will allow us to apply the law of conservation of energy.

1 Worked example

A toy car with a mass of 500 g is travelling at 3.00 m s^{-1}. Calculate the kinetic energy of the toy car.

Convert all values into SI units.

$m = 500\text{ g} = \frac{500}{1000}\text{ kg} = 0.500\text{ kg}$

$v = 3.00\text{ m s}^{-1}$

$KE = \frac{1}{2}mv^2$

$KE = \frac{1}{2} \times 0.500 \times 3.00^2$

$KE = 2.25\text{ J}$

Work done 3.3.14.1

OVERVIEW

Work is the change in the energy of an object caused by a force. The SI unit for work is joules (J) and work is a scalar quantity.

THEORY DETAILS

Work as a change in energy

As we know from Newton's first law, a change in the speed of an object (and therefore its kinetic energy) must be caused by a force. Work is a measure of the change in energy caused by a force. If given the energy of an object at two different locations, the work done can be calculated by subtracting the object's initial energy from the object's final energy.

In this lesson we focus on the relationship between work and kinetic energy (where $W = \Delta KE$). However, as we will see in later lessons, work is done when a force changes any form of energy.

2 Worked example

A 1500 kg car is initially travelling at 10 m s^{-1} and then speeds up to 30 m s^{-1}. Calculate the work done by the engine to speed up the car.

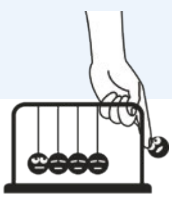
$KE_i = \frac{1}{2}mu^2 = \frac{1}{2} \times 1500 \times 10^2 = 75\,000\text{ J}$

$KE_f = \frac{1}{2}mv^2 = \frac{1}{2} \times 1500 \times 30^2 = 675\,000\text{ J}$

$W = KE_f - KE_i$

$W = 675\,000 - 75\,000$

$W = 6.0 \times 10^5\text{ J}$



Work as the product of a force and displacement

Work can also be defined and calculated as:

> $W = Fs$
>
> W = work done (J), F = magnitude of constant force (N), s = distance moved in the direction of force (m)

This equation gives a complementary definition of work which allows us to connect the ideas of force and energy. It is equivalent to stating that the kinetic energy of an object can change only when a force is applied parallel to the object's motion so it either speeds up or slows down. It also gives a more concrete understanding of **energy as the ability or potential to do work**.

In VCE Physics, we need to consider three situations where work is done by a constant force:

- If the distance moved is in the **same direction** as the applied force, energy is transferred **to the object**. This means the final energy (and speed) is greater than the initial energy (and speed). The work done will have a **positive** value.
- If the distance moved is in the **opposite direction** to the applied force, energy is transferred **from the object**. This means final energy (and speed) is less than initial energy (and speed). The work done will have a **negative** value.
- If the distance moved is **perpendicular** to the applied force, **no work** is done ($W = 0$).

If the applied force was on an angle relative to the displacement (which we will not need to consider in VCE Physics), then only the component of the force parallel to the displacement would do work.

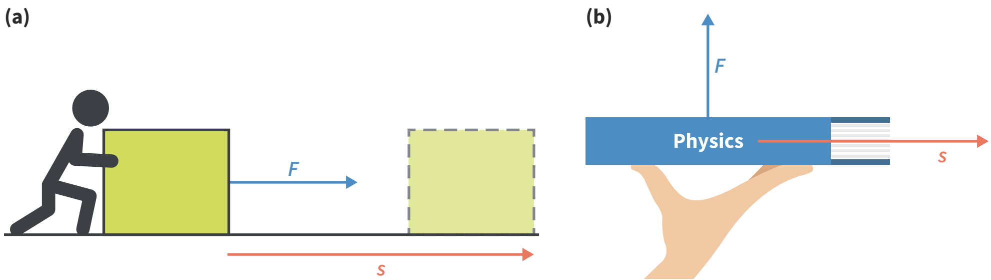


Figure 1 **(a)** By pushing a box positive work is done as the box moves in the same direction as the force. **(b)** When carrying a book horizontally 3 m to the right, no work is done as force and displacement are perpendicular.

Examples of work being done include:

- a car getting faster due to a driving force pushing the car in the direction of motion (positive work done).
- a car getting slower due to a brake force pushing the car against the direction of motion (negative work done).
- a bucket being lifted up a well by a rope due to the tension force on the bucket by the rope displacing the bucket upwards (positive work).

A person holding an object up in the air does **not** do work on that object (despite the fact that they may feel tired) because the force they apply does not result in the displacement of the object.

Multiple forces can do work on an object at once. If we push a box over a rough surface, the force we apply will do work which transfers kinetic energy to the box. At the same time, friction will act in the opposite direction and take kinetic energy away from the box. This energy will generally dissipate as sound and thermal energy.

3 Worked example

A person pushes a box across a horizontal surface by applying a force of 10 N in the direction of motion while a frictional force of 4.0 N acts on the box in the opposite direction. The box moves a distance of 5.0 m.

a **Calculate the work done on the box by the person.**

b **Calculate the work done on the box by friction.**

c **Calculate the total work done on the box.**

a The motion is in the same direction as the force applied by the person so we should expect a positive value for the work done on the box by the person.

$W_p = F_p s$

$W_p = 10 \times 5.0$

$W_p = 50$ J

b The motion is in the opposite direction to the frictional force so we should expect a negative value for the work done on the box by friction.

$W_f = F_f s$

$W_f = -4.0 \times 5.0$

$W_f = -20$ J

c The total work can be calculated in two ways. We can use the contributions of work done on the box by both the person and friction:

$W_{tot} = 50 - 20 = 30$ J

Alternatively we can use the net force in the formula for work done:

$W_{tot} = F_{net} s$

$W_{tot} = (10 - 4.0) \times 5.0$

$W_{tot} = 30$ J

This represents the total increase in kinetic energy of the box.

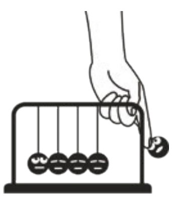
It is important to understand that the equation we have introduced in this section applies only to work being done by a constant force or to the average value of a changing force.

Calculating work from force-displacement graphs

When the force applied to an object is changing, the work done on the object can be determined by the area under a force-displacement. It cannot be determined using $W = Fs$. The explanation of why the work is equal to the area lies in integral calculus, which is beyond the scope of the VCE Physics course.

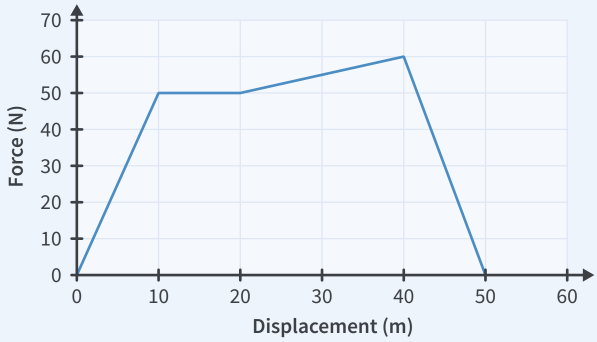
USEFUL TIP

Ensure that you check the units of the axes when calculating the area under a graph. You will need to convert units that are not in their SI form.



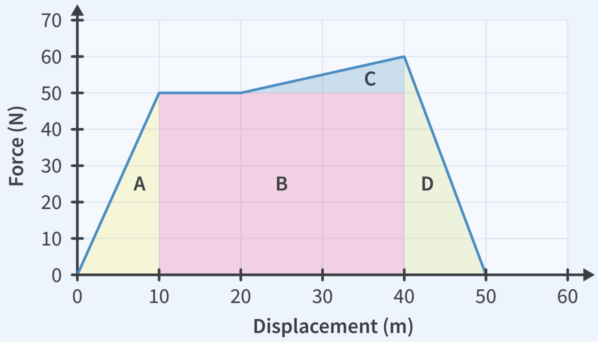
4 Worked example

Calculate the work done on an object that moves 50 metres in a constant direction, with an applied force that acts in the direction of motion and varies according to the force-displacement graph shown.



Work = area under force-displacement graph

First, divide the graph into areas made of rectangles and triangles.



Calculate the area of each rectangle/triangle.

$A_A = \frac{1}{2} \times 10 \times 50 = 250\text{ J}$

$A_B = 50 \times 30 = 1500\text{ J}$

$A_C = \frac{1}{2} \times 20 \times 10 = 100\text{ J}$

$A_D = \frac{1}{2} \times 10 \times 60 = 300\text{ J}$

Total area under graph = 250 + 1500 + 100 + 300 = 2150

Total work = 2150 J

Power as the rate of change in energy 2.1.15.1

OVERVIEW

Power is the rate of change of energy. The SI unit for power is watts (W) which is equivalent to joules per second (J s^{-1}). Power is a scalar quantity.

This knowledge unit is not explicitly included in Units 3 or 4 of VCE Physics but it is a fundamental concept which could reasonably be integrated into assessments in Units 3 or 4.

THEORY DETAILS

Power is related to change in energy and time by the following formula.

$$P = \frac{\Delta E}{\Delta t}$$

P = power (W), E = energy (J), t = time (s)

Power can also be viewed as the rate of work being done $\left(P = \frac{W}{\Delta t}\right)$ when the change in energy is caused by a force.

5 **Worked example**

An object gains 30 J of energy over the span of 1 minute. Calculate the power used during this energy transfer.

$\Delta E = 30$ J

$\Delta t = 1$ minute $= 60$ s

$P = \frac{\Delta E}{\Delta t} = \frac{30}{60} = 0.5$ W

Theory summary

- Kinetic energy is the energy of an object associated with its motion $\left(KE = \frac{1}{2}mv^2\right)$.
- Work is a change in energy caused by a force pushing parallel to the direction of motion ($W = Fs$).
  - When the force is in the same direction as motion, the work done is positive.
  - When the force is opposite to the direction of motion, the work done is negative.
- If an object has changed its kinetic energy, work has been done to the object.
- When the applied force is changing, work can be determined from the area under a force-displacement.
- Power is the rate of work being done or the rate of change of energy $\left(P = \frac{\Delta E}{\Delta t}\right)$

3B Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following best gives the kinetic energy of an object with a mass of 5.0 kg travelling at a speed of 8.0 m s^{-1}?

A 20 J

B 80 J

C 160 J

D 640 J

Question 2

In which of the following scenarios is the individual **not** doing work on an object?

A Sam picks up clothes from the floor.

B Jess holds a barbell above her head.

C Cassie pushes a pram.

D Ted opens a sliding door.

Question 3

An object initially has 4 J of kinetic energy. A while later, it has 12 J of kinetic energy. How much work has been done on the object?

A 3 J

B 4 J

C 8 J

D 12 J

Question 4

Which of the following best shows the work done by a person who applies a force of 35 N to open a sliding door a distance of 2 m?

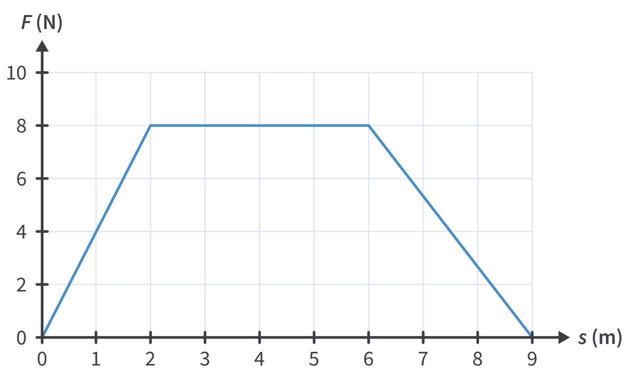
A 37 J

B 70 J

C 37 N m^{-1}

D 70 N m^{-1}

Question 5



Using the force-displacement graph, calculate the amount of work done.

A 25 J

B 26 J

C 52 J

D 72 J

EXAM-STYLE QUESTIONS

This lesson

Question 6 (4 MARKS)

a Calculate the work that has been done on an initially stationary car of mass 900 kg to get it moving at a speed of 10 m s^{-1}. (2 MARKS)

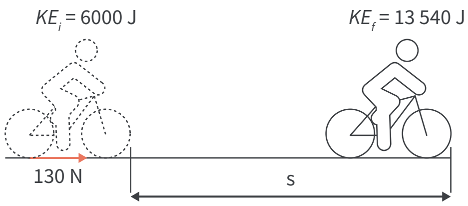
b Calculate the additional work that must be done to increase the speed of the car from 10 m s^{-1} to 20 m s^{-1}. (2 MARKS)

Question 7 (2 MARKS)

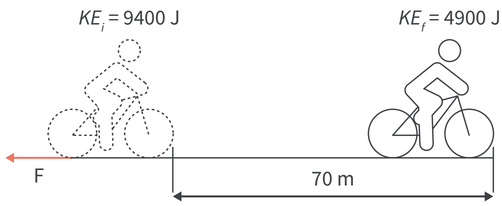
The combined mass of a cyclist and her bike is 80 kg. Calculate the final speed of the cyclist if she is travelling at 12 m s^{-1} and then does 10 240 J of work to increase her speed. Ignore the effects of resistance forces.

Question 8 (4 MARKS)

a A cyclist riding with an initial kinetic energy of 6000 J pedals such that the wheel pushes against the road with a constant force of 130 N to increase her kinetic energy to 13 540 J. Calculate the distance the cyclist travelled to achieve this increase in kinetic energy. Ignore the effects of resistance forces. (2 MARKS)

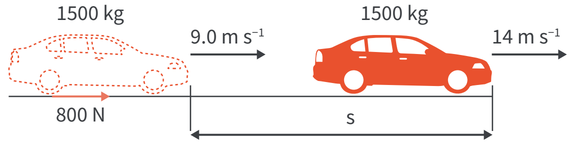


b Another cyclist riding with an initial kinetic energy of 9400 J applies a constant brake force to decrease his kinetic energy to 4900 J over a distance of 70 m. What is the magnitude of the braking force? Ignore the effects of resistance forces. (2 MARKS)

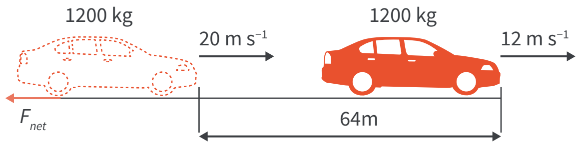


Question 9 (4 MARKS)

a A car with a mass of 1500 kg accelerates from a speed of 9.0 m s^{-1} to 14 m s^{-1} with a net force of magnitude 800 N. Calculate the distance over which the car achieves this increase in speed. Use the concept of work and energy. (2 MARKS)



b A car with a mass of 1200 kg slows from 20 m s^{-1} to 12 m s^{-1} by applying a constant brake force over a distance of 64 m. Calculate the magnitude of the net force applied to the car as it slows down. Use the concept of work and energy. (2 MARKS)



Question 10 (3 MARKS)

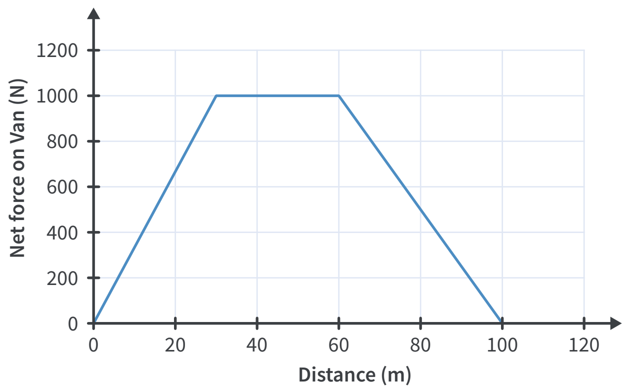
Brake tests for a new car are conducted where the same brake force is applied in each trial (controlled variable) for a car travelling at two different speeds. The distance to stop is measured.

	Initial speed (independent variable)	Distance to stop (dependent variable)
Trial A	5 m s^{-1}	2 m
Trial B	15 m s^{-1}	18 m

Explain why a car that is moving 3 times faster takes 9 times the distance to stop, given that the same brake force is applied. Use the concepts of work and energy in your explanation.

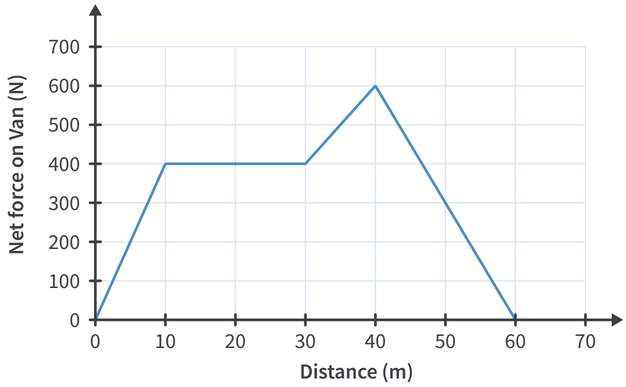
Question 11 (3 MARKS)

The graph shows the net force applied to a van with a mass of 1600 kg which is initially moving at a speed of 8.0 m s^{-1}. The net force is in the direction of motion. Calculate the final speed of the van after it has travelled 100 m.



Question 12 (3 MARKS)

A 1300 kg car passes through an intersection (which corresponds to a distance of 0 metres on the graph shown) at a speed of 36.0 km h^{-1}. The driver varies the application of the accelerator so that the net force in the direction of the car's motion varies as shown in the graph. The distance is measured from the intersection.



Use the graph to calculate the speed of the car after it has travelled 60.0 m.

Question 13 (3 MARKS)

Genevieve (60.0 kg) is riding a bike (20.0 kg), and she increases her speed from 10.0 km h^{-1} to 15.0 km h^{-1} over 3.00 minutes on a flat road. Calculate the power exerted by Genevieve. Ignore the effects of any resistance forces.

Question 14 (6 MARKS)

A removalist pushes a heavy box on a rough surface such that the net force on the box is 50.0 N. The removalist pushes with a power of 300 W for 30.0 seconds and moves the box 15.0 m. There is a constant friction force acting against the motion of the box causing energy to dissipate as heat.

a Calculate the magnitude of the force applied by the removalist. (3 MARKS)

b Calculate the magnitude of the friction force. (1 MARK)

c Calculate the amount of energy dissipated as heat. (2 MARKS)

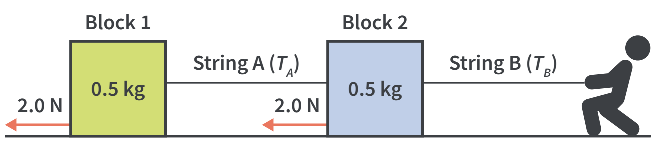
Previous lessons

Question 15 (5 MARKS)

A child is pulling a toy, which consists of two blocks connected by string, along the ground. The mass of each block is 0.50 kg and each block experiences a friction force of 2.0 N.

T_A and T_B are the tensions in the strings as shown in the diagram.

The child and the toy are moving towards the **right**.



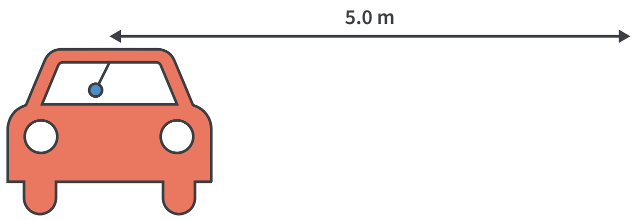
a Calculate the magnitude of T_B when the child is pulling the blocks at constant velocity. (1 MARK)

b The child then accelerates at a rate of 0.80 m s^{-2}. Calculate the magnitude of T_A. (2 MARKS)

c The strings will break if the tension reaches 10 N. The child drags the blocks at an increasing acceleration until one of the strings breaks. Calculate the magnitude of the acceleration when this occurs. Assume that the friction on each block remains the same (2.0 N on each). (2 MARKS)

Question 16 (7 MARKS)

A car drives at a constant speed of 3.0 m s^{-1} around a roundabout with a radius of 5.0 m. Inside the car there is a ball with a mass of 0.15 kg hanging on a piece of string from the roof.



a What is the magnitude of the net force on the ball? (1 MARK)

b Copy the diagram of the ball on the string and draw arrows to show the forces acting on the ball. Also include a dashed arrow to show the net force on the ball. (2 MARKS)

Adapted from 2013 VCAA Exam Section A Q4a

c Explain how the forces acting on the ball cause the net force. (2 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 1 Q5

d What angle does the string make with the vertical? (2 MARKS)

Key science skills

Question 17 (3 MARKS)

Mikaela, Sergio and Liam are investigating work and kinetic energy. They measure the speed of a cart after a force has been applied using a ruler and a stopwatch. Mikaela suggests that it is important to repeat the measurement to reduce the effects of random error. Sergio agrees that they should repeat the measurement, but he suggests this will reduce the effects of systematic error. Liam suggests that repeating the measurement will reduce the absolute uncertainty of each measured value.

Evaluate each of these three claims.

3C ELASTIC AND INELASTIC COLLISIONS

In this lesson we will analyse collisions in one dimension and classify them as either elastic or inelastic. We will investigate the conservation of momentum and determine the possible changes in kinetic energy during collisions.

3A Momentum and impulse	3B Kinetic energy, work and power	3C Elastic and inelastic collisions	3D Gravitational potential energy	3E Strain potential energy	3F Vertical spring-mass systems

Study design key knowledge dot points

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

Key knowledge units

Elastic and inelastic collisions	3.3.6.2 & 3.3.15.6
Energy dissipation	3.3.15.5

Formulas for this lesson

Previous lessons		New formulas
3A	* $p = mv$	No new formulas in this lesson
3A	$p_i = p_f$	
3B	* $KE = \frac{1}{2}mv^2$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

elastic collision a collision in which kinetic energy is conserved

energy dissipation the transfer of energy out of a system

inelastic collision a collision in which kinetic energy is not conserved

Elastic and inelastic collisions 3.3.6.2 & 3.3.15.6

OVERVIEW

Momentum is conserved in all collisions. In elastic collisions kinetic energy is also conserved, whereas in inelastic conditions kinetic energy is not conserved.

THEORY DETAILS

Total momentum is conserved in all collisions. This means that the sum of the initial momenta of objects involved in a collision is equal to the sum of the final momenta of the same objects after a collision.

USEFUL TIP

Momentum is a vector quantity. When calculating the total momentum before and after a collision, make sure to take into account the direction of movement.

Elastic collisions

In elastic collisions, **kinetic energy is conserved**. This means that the total kinetic energy of the colliding objects before the collision is equal to the total kinetic energy of the objects after the collision. As in all collisions, momentum is also conserved.

Not many everyday collisions are elastic: true elastic collisions only occur at a subatomic level. However, collisions between very rigid objects like billiard balls are often close to elastic collisions.

Inelastic collisions

During inelastic collisions, **kinetic energy is not conserved**. This means that the total kinetic energy of the colliding objects before the collision is not equal to the total kinetic energy of the objects after the collision, despite momentum still being conserved. Since kinetic energy cannot be gained in a collision, the total kinetic energy after an inelastic collision will be less than before the collision. This is because the kinetic energy lost in the collision is transformed into other types of energy.

Most collisions in the real world are inelastic collisions, such as a car crash or football players tackling each other.

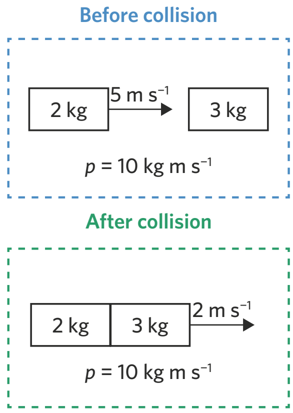


Figure 1 The total momentum of objects involved in a collision is the same before and after the collision occurs.

Problem solving process

To solve common VCAA collision questions:

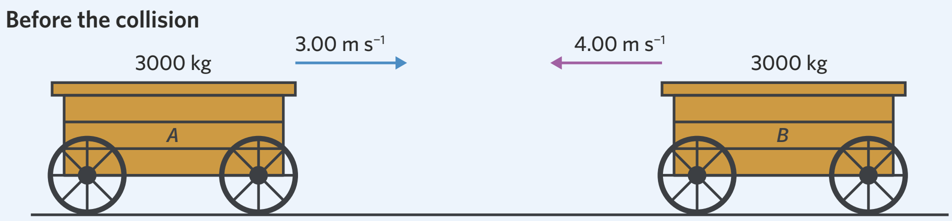
1. Calculate total momentum before collision.
2. Using the conservation of momentum and information provided, calculate the final velocity of the colliding objects.
3. Calculate the total kinetic energy before and after the collision.
4. From the change in kinetic energy, determine if the collision conserved kinetic energy (elastic) or did not (inelastic).

USEFUL TIP

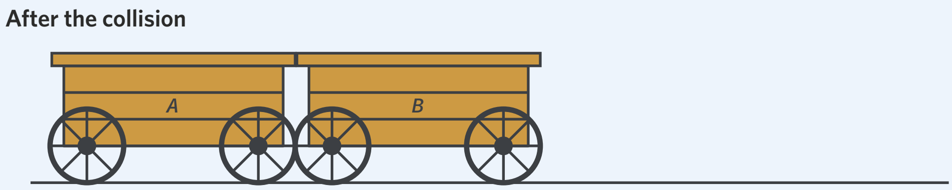
If the final total kinetic energy is larger than the initial total kinetic energy, you have made a mistake in your working.

1 Worked example

Two 3000 kg train cars, car *A* and car *B*, are moving toward each other head on. Before they collide, car *A* is travelling to the right at 3.00 m s^{-1} and car *B* is travelling to the left at 4.00 m s^{-1}.



After the collision, the cars are joined together and move off as one.



a **Calculate the final velocity of the joined cars.**

b **Is the collision elastic or inelastic? Justify your answer with calculations.**

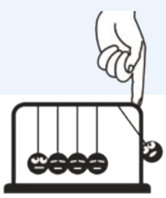
a Define the right direction as positive.

Initial total momentum:

$p = mv \ \therefore p_A = m_A \times u_A = 3000 \times 3.00 = 9000$ kg m s^{-1}

$p_B = m_B \times u_B = 3000 \times -4.00 = -12\,000$ kg m s^{-1}

$p_{tot} = p_A + p_B = 9000 - 12\,000 = -3000$ kg m s^{-1} (negative value indicates direction is to the left)



Final total momentum:

$p_f = p_i \therefore p_f = -3000$ kg m s^{-1} (negative value indicates direction is to the left)

Final velocity:

$p_f = (m_A + m_B) \times v_f \therefore -3000 = (3000 + 3000) \times v_f$

$v_f = \frac{-3000}{(3000 + 3000)} = -0.500$ m s^{-1} (negative value indicates direction is to the left)

b Initial total kinetic energy:

$KE_A = \frac{1}{2} m_A u_A{}^2 = \frac{1}{2} \times 3000 \times 3.00^2 = 13\,500$ J

$KE_B = \frac{1}{2} m_B u_B{}^2 = \frac{1}{2} \times 3000 \times 4.00^2 = 24\,000$ J

$KE_{tot} = KE_A + KE_B = 13\,500 + 24\,000 = 37\,500$ J

Final total kinetic energy:

$KE_{tot} = KE_A + KE_B = \frac{1}{2} m_A v_A{}^2 + \frac{1}{2} m_B v_B{}^2 = 2 \times \frac{1}{2} \times 3000 \times 0.500^2 = 750$ J

Compare initial and final total kinetic energy:

$KE_i \neq KE_f$ therefore it is an inelastic collision.

Note that kinetic energy is **not** a vector quantity. No matter the direction objects are travelling before or after a collision, kinetic energy is always added to find the total.

Energy dissipation 3.3.15.5

OVERVIEW

During inelastic collisions, the kinetic energy lost is dissipated from the objects in the form of heat, sound, and the deformation of the objects.

THEORY DETAILS

During collisions where kinetic energy is not conserved (inelastic collisions), the energy lost must be transformed into other forms of energy, since energy cannot just vanish.

Imagine a tennis ball bouncing along the floor. With each bounce, the tennis ball loses kinetic energy, which can be seen by the ball bouncing lower each time. We know that there will be a sound produced as the ball bounces, and the energy required to produce this sound comes from the kinetic energy of the ball. Additionally, there will be friction between the tennis ball and the ground, which generates heat. This heat energy is also transformed from the initial kinetic energy of the ball. Finally, with each bounce energy is transformed into deformation of the tennis ball (changing its shape).

Due to processes like the ones seen in the tennis ball bounce, kinetic energy is dissipated into other forms during inelastic collisions. To observe energy dissipation yourself, try rubbing your hands together. The kinetic energy of your hands will be transformed into heat energy due to friction.

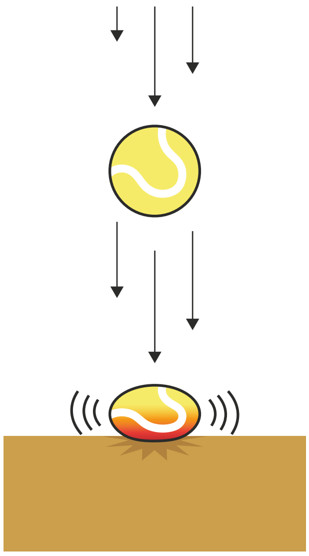


Figure 2 Energy is dissipated as sound, heat, and deformation of the tennis ball when it collides with the ground.

Theory summary

- The total momentum is conserved in all collisions
- Kinetic energy is conserved in elastic collisions
- Kinetic energy is not conserved (decreases) in inelastic collisions
- When energy is not conserved, it is dissipated in the form of heat, sound or object deformation

KEEN TO INVESTIGATE?

oPhysics 'Momentum & Energy: Elastic and Inelastic Collisions' simulation
https://ophysics.com/e2.html

oPhysics 'Momentum & Energy: Explosive "Collisions"' simulation
https://ophysics.com/e2a.html

PhET 'Collision Lab' simulation
https://phet.colorado.edu/sims/collision-lab/collision-lab_en.html

3C Questions

THEORY REVIEW QUESTIONS

Question 1

Choose the row that best describes types of collisions:

	Collision	Momentum conserved?	Kinetic energy conserved?
A	Elastic	Yes	Yes
	Inelastic	Yes	Yes
B	Elastic	Yes	Yes
	Inelastic	Yes	No
C	Elastic	No	Yes
	Inelastic	Yes	No
D	Elastic	Yes	No
	Inelastic	Yes	Yes

Question 2

Which of the following statements is incorrect?

A Energy is a vector quantity. When calculating total energy, you should keep in mind the directional sign.

B Energy is a scalar quantity. When calculating total energy, always add the various energies together.

C Momentum is a vector quantity. When calculating total momentum, you should keep in mind the directional sign.

D Energy is dissipated away from inelastic collisions.

EXAM-STYLE QUESTIONS

This lesson

Question 3 (8 MARKS)

Two whitetail bucks are charging towards each other and collide **head on** during a territorial fight. Before the collision, buck *A* has a mass of 110 kg and is moving at 8.00 m s^{-1} to the right, while buck *B* is 130 kg and is moving at 5.00 m s^{-1} to the left.

a What is the total momentum before the bucks collide? (1 MARK)

b What will be the total momentum after the collision? (1 MARK)

c After the collision, buck *A* and *B* are locked together. At what speed are the joined pair travelling? (2 MARKS)

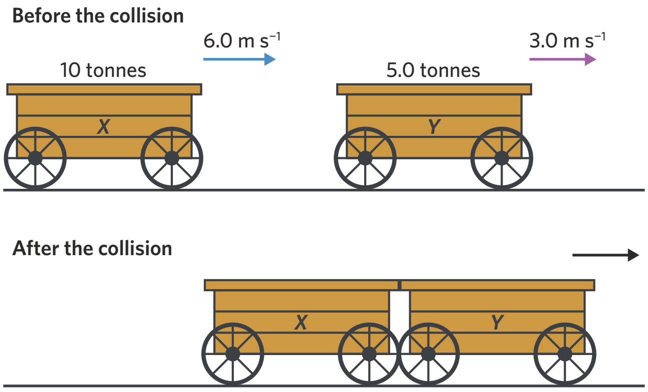
d Calculate the initial total kinetic energy of the two bucks. (2 MARKS)

e Calculate the final total kinetic energy of the two bucks. (1 MARK)

f Is the collision elastic or inelastic? (1 MARK)

Question 4 (5 MARKS)

Two runaway train cars collide and join together.



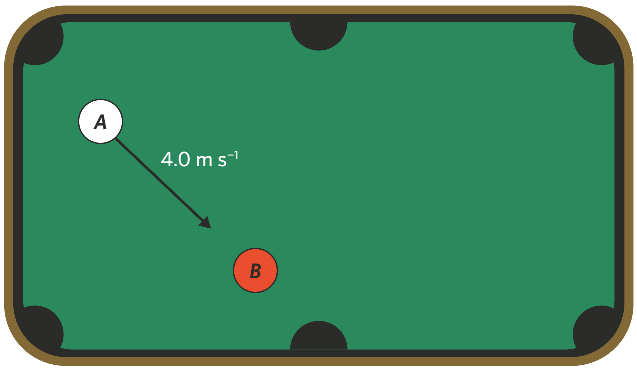
a Calculate the final speed of the joined cars. (2 MARKS)

b Is the collision elastic or inelastic? Use calculations to support your answer. (3 MARKS)

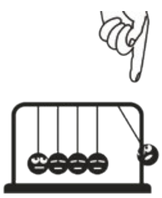
Adapted from 2018 VCAA Exam Section A Q8

Question 5 (3 MARKS)

Two billiard balls collide during a game of pool. They each have a mass of 0.35 kg and ball *A* has an initial speed of 4.0 m s^{-1} before it hits the stationary ball *B*.



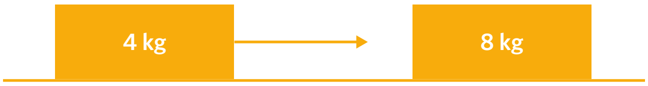
After the collision ball *A* is stationary. Find the final speed of ball *B* and determine, using calculations, if the collision is elastic or inelastic.



Question 6 (3 MARKS)

Two blocks collide on a frictionless surface. Initially, a 4 kg block is travelling to the right, before it collides elastically with an 8 kg block.

Before collision



After they collide, the 8 kg block moves to the right and the 4 kg block moves to the left as shown in the diagram.

After collision

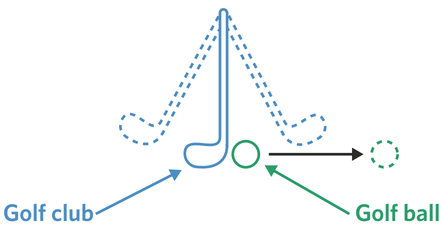
The magnitude of the momentum of the 8 kg block after the collision is **greater** than the magnitude of the momentum that the 4 kg block had before the collision.

Explain why the greater magnitude momentum of the 8 kg block is consistent with the law of conservation of momentum.

Adapted from 2012 VCAA Exam 1 Section A AoS 1 Q2

Question 7 (4 MARKS)

The behaviour of a golf ball and the club used to strike it is being investigated. Treat the impact as an elastic collision between the head of the golf club and the golf ball.



Four relevant measurements are recorded.

Mass of golf ball	48 g
Initial speed of golf club head	30.00 m s^{-1}
Final speed of golf club head	24.74 m s^{-1}
Final speed of golf ball	54.74 m s^{-1}

Given that the golf ball was stationary before being hit, calculate the mass (in grams) of the golf club head.

Previous lessons

Question 8 (2 MARKS)

A motorcycle rider drives around a banked circular track which is angled at 25° to the horizontal. The rider's circular path has a radius of 50 m.

a Calculate the speed they should drive at so that they do not experience a sideways frictional force while maintaining this path. (1 MARK)

b Calculate the required angle of the banked track for there to be no sideways friction force if the rider drives at 30 m s^{-1} along the same circular path. (1 MARK)

Question 9 (2 MARKS)

Calculate the impulse given to a 0.25 kg toy rocket when it is accelerated from rest to 60 m s^{-1} by a strong spring.

Key science skills

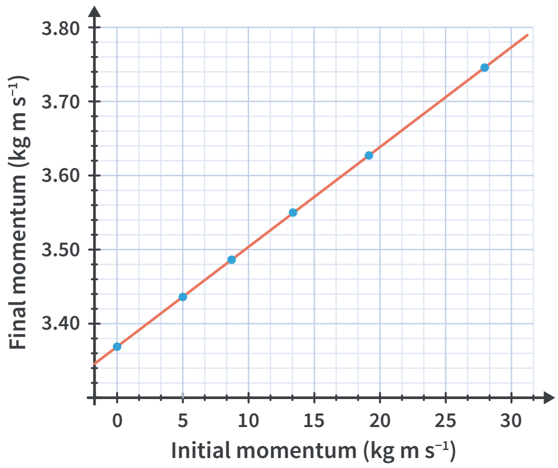
Question 10 (2 MARKS)

Five different momentum measurements are recorded. Determine the number of significant figures used for each of the values:

0.50001 kg m s^{-1}, 0.00001 kg m s^{-1}, 0.500 kg m s^{-1}, 0.50×10^7 kg m s^{-1}, 0.001×10^{-3} kg m s^{-1}, 420 kg m s^{-1}.

Question 11 (2 MARKS)

Describe the gradient of this final momentum versus initial momentum graph.



3D GRAVITATIONAL POTENTIAL ENERGY

This lesson will build on our understanding of work and energy from lesson 3B. Gravitational potential energy is the energy associated with the position of an object within a gravitational field. We will introduce the law of conservation of energy and use it as a convenient way to relate the change in an object's height to its associated change in speed.

3A Momentum and impulse	3B Kinetic energy, work and power	3C Elastic and inelastic collisions	3D Gravitational potential energy	3E Strain potential energy	3F Vertical spring-mass systems

Study design key knowledge dot point

- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

Key knowledge units

Gravitational potential energy	3.3.15.2
Conservation of energy	3.3.15.4

Formulas for this lesson

	Previous lessons	New formulas
3B	* $KE = \frac{1}{2}mv^2$	* $\Delta GPE = mg\Delta h$
3B	$W = Fs$	$v = \sqrt{-2g\Delta h + u^2}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

gravitational potential energy the stored energy associated with the position of an object in a gravitational field

Gravitational potential energy 3.3.15.2

OVERVIEW

Gravitational potential energy is the energy associated with the position of an object within a gravitational field. We can calculate the change in gravitational potential energy when an object changes its height in the field with $\Delta GPE = mg\Delta h$.

THEORY DETAILS

In lesson 3B we learned that work is done whenever a force is applied to an object in a parallel direction to its motion – such as the force due to gravity acting on a falling object – and it can be calculated from the equation $W = Fs$ or by the area under a force-displacement graph. For a uniform gravitational field, the force due to gravity acting on a given object is constant. Figure 1 shows a force-displacement graph for a 2 kg object under the influence of a uniform gravitational field with strength 9.8 N kg^{-1}.

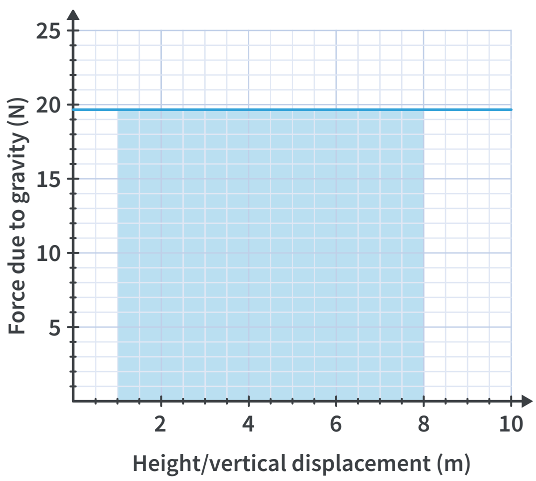


Figure 1 A force-displacement graph for a 2 kg object. The force due to gravity remains constant so the graph shows a horizontal line. The shaded area represents the work done, or the change in gravitational potential energy.

We also know from lesson 3B that the work done is equal to the change in energy of an object caused by a force. Gravitational potential energy represents the object's potential to do work due to its height in a gravitational field.

This means the area under a gravitational force-height graph will give us the magnitude of the **change** in gravitational potential energy ($W = \Delta GPE$). The change in height (vertical displacement) of the object is $h_f - h_i = \Delta h$. The force due to gravity is given by $F_g = mg$.

Since the area under the graph is a rectangle, we multiply the force (mg) with the change in height (Δh) to get the change in gravitational potential energy.

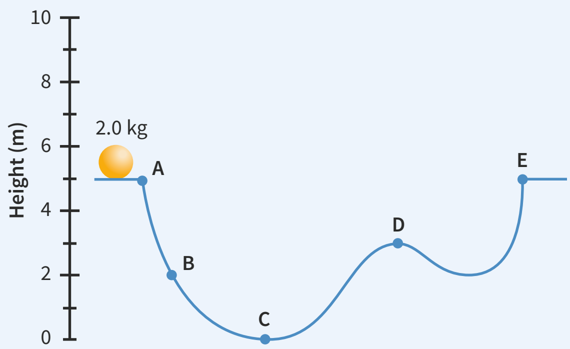
$$\Delta GPE = mg\Delta h$$

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*.

1 **Worked example**

A 2.0 kilogram ball is released from the top of a track with an initial height of 5.0 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 from point A to the points B, C, and E?

Point B:
We are given the mass $m = 2.0$ kg, acceleration due to gravity $g = 9.8$ m s^{-2}

$\Delta h = h_f - h_i = 2 - 5 \therefore \Delta h = -3$ m

$\Delta GPE = mg\Delta h = 2.0 \times 9.8 \times (-3)$

$\Delta GPE = -59$ J

As the question asks for the magnitide, we take a positive value.

$\Delta GPE = 59$ J

Point C:
We are given the mass $m = 2.0$ kg, acceleration due to gravity $g = 9.8$ m s^{-2}

$\Delta h = h_f - h_i = 0 - 5 \therefore \Delta h = -5$ m

$\Delta GPE = mg\Delta h = 2.0 \times 9.8 \times (-5)$

$\Delta GPE = -98$ J

As the question asks for the magnitude, we take a positive value.

$\Delta GPE = 98$ J

Point E:
We are given the mass $m = 2.0$ kg, acceleration due to gravity $g = 9.8$ m s^{-2}

$\Delta h = h_f - h_i = 5 - 5 \therefore \Delta h = 0$ m

$\Delta GPE = mg\Delta h = 2.0 \times 9.8 \times 0$

$\Delta GPE = 0$ J

Conservation of energy 3.3.15.4

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.

We can expand the energy conservation equation by substituting in the values 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 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:

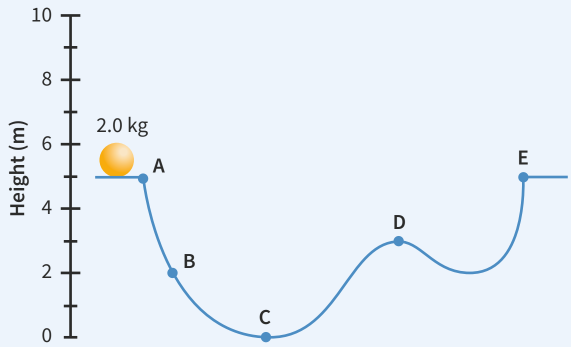
$$v = \sqrt{-2g\Delta h + u^2}$$

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})

Energy can be transformed into other types like thermal energy, sound energy, and deformation of material. This is called energy dissipation and it does not violate the conservation of energy principle.

2 Worked example

A 2.0 kilogram ball is released from the top of a track with an initial height of 5.0 m as shown in the diagram. Its speed is initially zero. Take the gravitational potential energy at the bottom to be zero.



Calculate:

a **the gravitational potential energy at point A.**

b **the kinetic energy at point B.**

c **the speed at point C.**

d **the total energy at point D.**

a We are given: the mass $m = 2.0$ kg, gravitational acceleration $g = 9.8$ m s^{-2}, and height $h = 5.0$ m (measured relative to the ground).

$GPE = mgh = 2.0 \times 9.8 \times 5.0$

$GPE = 98$ J

b $KE_A + GPE_A = KE_B + GPE_B$ where $KE_i = 0$

$GPE_A = KE_B + GPE_B$

$98 = KE_B + 2.0 \times 9.8 \times 2$

$98 = KE_B + 39.2$

$KE_B = 98 - 39.2$

$KE_f = 59$ J

c $g = 9.8$ m s^{-2}, $h_i = 5.0$ m, $h_f = 0$ m, $u = 0$ m s^{-1}

Substitute into the equation: $v = \sqrt{-2g\Delta h + u^2}$

$v = \sqrt{-2 \times 9.8 \times (0-5) + 0^2}$

$v = 9.9$ m s^{-1}

d The total energy is the same at all points. So we will use point A to find the total energy.

At point A: $E = KE + GPE$, where $KE = 0$

$E = 0 + 98 = 98$ J

Theory summary

- A change in gravitational potential energy can be calculated from
  - the area under a gravitational force-height graph.
  - the equation $\Delta GPE = mg\Delta h$.
- Energy is always conserved.
  - The initial energy equals the final energy of the system. For a system involving only kinetic energy and gravitational potential energy this gives us: $KE_i + GPE_i = KE_f + GPE_f$
  - $v = \sqrt{-2g\Delta h + u^2}$
- In the real world energy is often transformed into other forms such as thermal energy and sound.

KEEN TO INVESTIGATE?

PhET 'Energy Skate Park' simulation
https://phet.colorado.edu/en/simulation/energy-skate-park-basics

3D Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following statements is correct?

A Total energy is always conserved.

B Total energy is only conserved in frictionless systems.

C Gravitational potential energy is always conserved.

D Total energy is not conserved.

Question 2

An object is dropped 1 m with an initial gravitational potential energy of 15 J and a final gravitational potential energy of 12 J. Which equation would we use to find the change in the object's kinetic energy?

A $\Delta KE = \frac{1}{2}m(u^2 - v^2)$

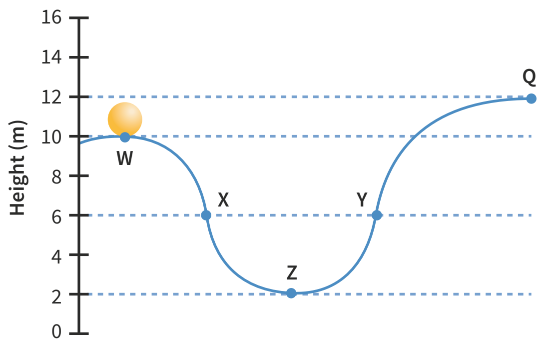
B $\Delta KE = \frac{1}{2}mu^2 - \frac{1}{2}mv^2$

C $KE = GPE$

D $KE_i + GPE_i = KE_f + GPE_f$

Use the following information to answer Questions 3–6.

A 15 kg ball which is initially at rest at point W rolls along the frictionless track shown in the diagram.



Question 3

Which of the following calculations could be used to find the change in gravitational potential energy as the ball rolls from point W to point X?

A $15 \times 10 \times g$

B $15 \times 6 \times g$

C $15 \times (10 - 6) \times g$

D $15 \times (10 - 2) \times g$

Question 4

At which two points is the ball moving at the same speed?

A W and Q

B X and Y

C X and Z

D Y and Z

Question 5

Which of the following calculations could be used to find the kinetic energy of the ball at point Z?

A $15 \times (10 - 2) \times g$

B $\frac{1}{2} \times 15 \times 3^2$

C $15 \times 10 \times g$

D $\frac{1}{2} \times 15 \times 8^2$

Question 6

Which of the following options is the best reason the ball never reaches point Q?

A The gravitational potential energy at point Q is greater than the total energy of the ball.

B Friction would cause the ball to stop before it reaches point Q.

C The ball does not have enough mass to make it over the second hill.

D The horizontal distance to point Q is too far.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (4 MARKS)

A 1800 kg jeep is travelling at 30 m s^{-1} at the bottom of a 15 m hill. Assume there is no friction and no driving force acting on the car.

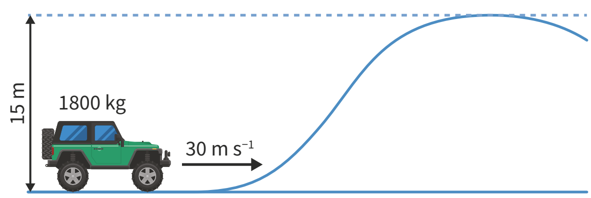


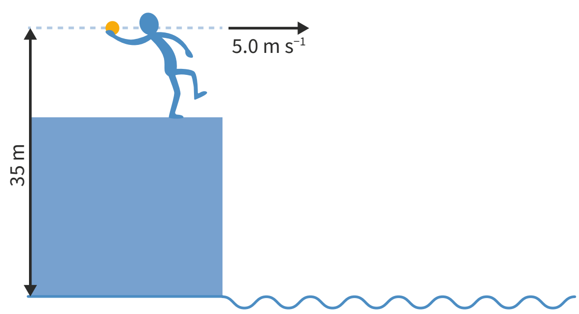
Image: EgudinKa/Shutterstock.com

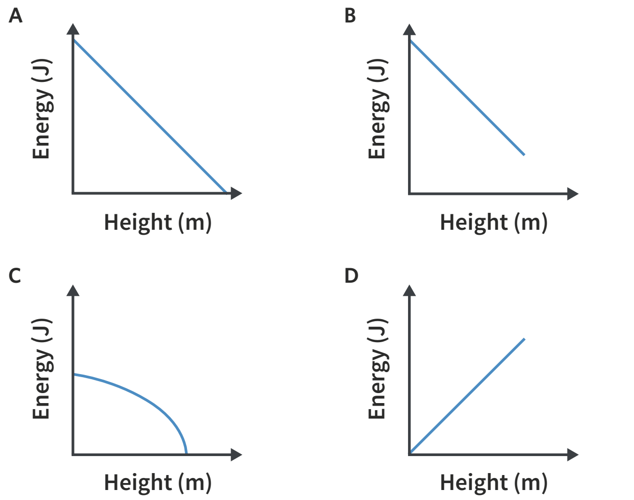
a Calculate the change in gravitational potential energy of the car when it reaches the top of the hill. (2 MARKS)

b Calculate how fast the car is travelling when it reaches the top of the hill. (2 MARKS)

Question 8 (8 MARKS)

Tom throws a 0.50 kg ball at 5.0 m s^{-1} from a height of 35 m. Take the gravitational potential energy at the water to be zero.





a Which graph (A-D) best shows the kinetic energy of the ball as a function of height? Explain your answer. (2 MARKS)

b Which graph (A-D) best shows the gravitational potential energy of the ball as a function of height? Explain your answer. (2 MARKS)

c What is the kinetic energy of the ball when it impacts the water? (2 MARKS)

d What is the speed of the ball when it is 10 metres above the water? (2 MARKS)

Question 9 (5 MARKS)

Lucie, a 64 kg skier rides down a frictionless mountain side until she reaches a dirt patch at the bottom. The dirt slows Lucie to a complete stop with a force of 560 N applied over 18.2 m.

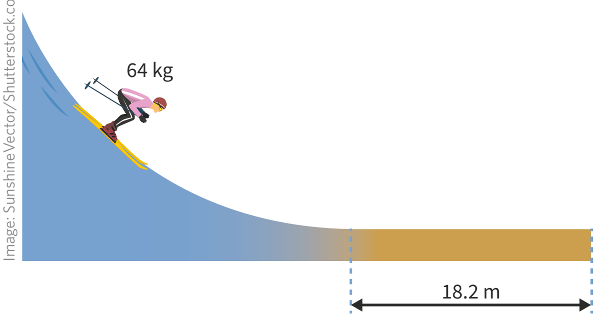


Image: SunshineVector/Shutterstock.com

a What is the height of the hill Lucie skied down? (3 MARKS)

b Is energy conserved when moving over the dirt patch? Explain your answer. (2 MARKS)

Question 10 (3 MARKS)

A probe of mass 1.5 kg, which is initially at rest, drops from a height of 4.0 m above the surface of the Moon. Take the moon to have a gravitational field strength, g, of 1.5 m s^{-2}.

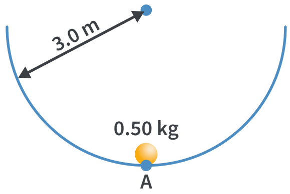
Sketch gravitational potential energy and kinetic energy as a function of height above the Moon's surface. Take the gravitational potential energy on the surface of the moon to be zero.

Adapted from 2017 VCAA Sample Exam Section B Q1b

Previous lessons

Question 11 (3 MARKS)

A 0.50 kg ball is on a vertical circular track of radius 3.0 m. At the lowest point A, the ball is moving at 8.0 m s^{-1}. Ignore air resistance.



a Draw the resultant force acting on the ball at point A. (1 MARK)

b What is the magnitude of the force that the ball exerts on the track at point A? (2 MARKS)

Adapted from 2015 VCAA Exam Section A Q3

Question 12 (5 MARKS)

A baseball fielder attempts to catch a ball. The ball has a mass of 0.250 kg.

Speed of ball before collision	13.0 m s^{-1}
Speed of ball after collision	0 m s^{-1}
Time in contact with the ball	0.150 s

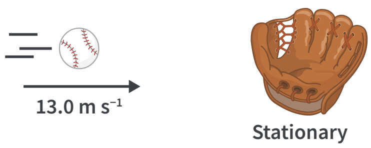


Image: Yayayoyo/Shutterstock.com

a Calculate the magnitude of the impulse given by the glove to the ball. Give your answer in appropriate units. (3 MARKS)

b Calculate the magnitude of the average force by the glove on the ball during the collision. Show your working. (2 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q7

Key science skills

Question 13 (6 MARKS)

Students drop a 0.50 kg ball from rest at varying heights and record the final kinetic energy of the ball just before it hits the ground. Take the ground as the position with zero gravitational potential energy.

a Calculate the values for the initial gravitational potential energy and write them in a similar table in your book. (2 MARKS)

Height from which the ball is dropped (m)	Initial gravitational potential energy (J)	Final kinetic energy (J)
2		9.5
4		18
6		27
8		35

b Draw a graph of the final kinetic energy on the vertical axis versus the initial gravitational potential energy on the horizontal axis using the data from the table in part **a**. You must also provide an appropriate label for each axis, a scale, and a line of best fit. (4 MARKS)

3E STRAIN POTENTIAL ENERGY

A spring will always produce a force to return to its natural length. We can plot the force-displacement graph for a spring and find the area under the graph to calculate strain potential energy. Strain potential energy will be used in conservation of energy calculations alongside gravitational potential energy and kinetic energy.

Study design key knowledge dot point

- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}kx^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

Key knowledge units

Hooke's law	3.3.15.3.1
Strain potential energy	3.3.15.3.2

Formulas for this lesson

Previous lessons		New formulas
2B	$F_g = mg$	* $F_s = -k\Delta x$
3B	* $KE = \frac{1}{2}mv^2$	* $SPE = \frac{1}{2}k(\Delta x)^2$
3D	* $\Delta GPE = mg\Delta h$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

compression (spring) 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 3.3.15.3.1

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 a spring.

THEORY DETAILS

Hooke's law is used to calculate the restoring force that an ideal spring applies when it is compressed or extended.

$F_s = -k\Delta x$

F_s = spring restoring force (N), k = spring constant (N m^{-1}), Δx = displacement from natural position (m)

- A spring will always produce a force in the opposite direction to its displacement to return to its natural length which is represented by the negative sign.
- When a spring is in its natural position (neither compressed nor stretched, $\Delta x = 0$) it will not exert a force ($F_s = k\Delta x = 0$).
- The spring constant is a property of each spring and it is equal to the gradient of a spring's force-displacement graph (Figure 1).
- Many elastic objects besides springs may obey Hooke's law, but springs will be the most common in VCE Physics.

USEFUL TIP

In VCE Physics it is common to deal with the magnitudes of forces, in which case the negative sign in Hooke's law can be excluded. Hence, we would use $F_s = k\Delta x$ in our calculations.

Equilibrium involving springs

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.

- When dropped from a height, the equilibrium position is where the object reaches its maximum speed.
- This is the only position where an object can remain stationary over time.

Note that if the velocity of a mass is zero, it does not necessarily mean that the spring is in equilibrium. This will be covered in more detail in lesson 3F.

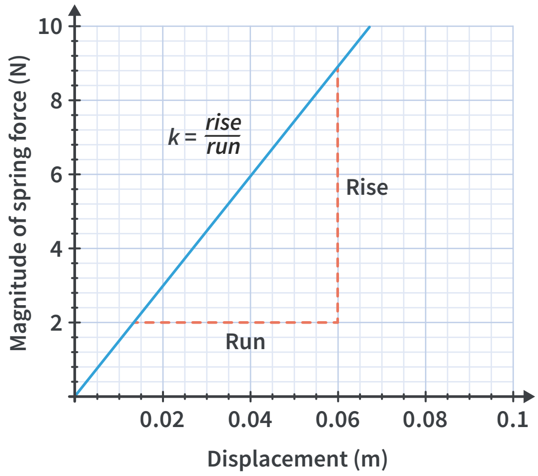
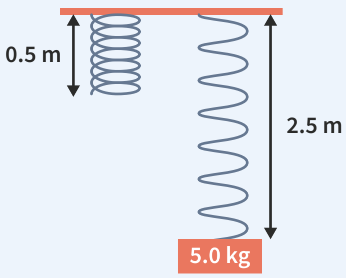


Figure 1 The spring restoring force against displacement from the spring's natural length. The gradient is the spring constant, k.

1 **Worked example**

To determine the spring constant of a spring, students attached a block with a mass of 5.0 kg to a hanging spring. The diagram on the left shows the uncompressed spring and the diagram on the right shows the spring with the block at rest hanging on the spring.



a **What is the magnitude of the displacement, Δx, of the spring from its natural state?**

b **Find the spring constant, k.**

a Δx is the magnitude of the displacement from the uncompressed spring.

$\Delta x = 2.5 - 0.5$

$\Delta x = 2.0$ m

b The block is in equilibrium since it is **at rest** so the magnitudes of the force due to gravity and the spring force must be equal.

$F_s = F_g$

$mg = k\Delta x$

$5.0 \times 9.8 = k \times 2.0$

$k = 25$ N m^{-1}

Strain potential energy 3.3.15.3.2

OVERVIEW

Strain potential energy is equal to the area under a force-displacement graph for a spring and it represents the energy that is stored in the spring. It can be transformed into gravitational potential energy, kinetic energy, or dissipated into the environment according to the law of conservation of energy described in lesson 3D.

THEORY DETAILS

In lesson 3B we learned that work is done whenever a force is applied to an object in a parallel direction to its motion – such as the force applied to compress or stretch a spring – and is equal to the area under a force-displacement graph.

We also know from lesson 3B that the work done is equal to the change in energy of an object caused by a force. Strain potential energy represents the spring's potential to do work as it returns to its natural length.

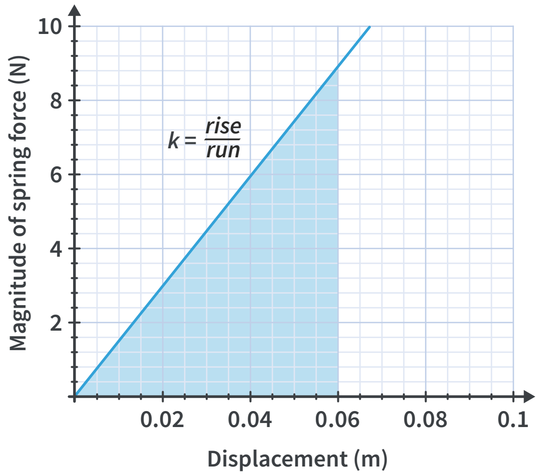


Figure 2 The shaded area shows the strain potential energy when the spring is displaced 0.06 m from its natural state.

This means the area under the force-displacement graph for a spring will give us the change in strain potential energy ($W = \Delta SPE$). When the spring is stretched or compressed from its natural length, the area under the graph is a triangle so it can be calculated according to $\frac{1}{2} \times base \times height = \frac{1}{2} \times \Delta x \times F_s$. By substituting $k\Delta x$ in the place of F_s, we arrive at the following formula for the strain 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. For the purposes of making an obvious distinction between different forms of energy, this book will usually use *SPE*.

USEFUL TIP

Strain potential energy is also known as elastic potential energy or spring potential energy.

Conservation of energy

As we learned in lesson 3D, total energy 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 equal to zero.

For example: $SPE_i = KE_f + GPE_f$

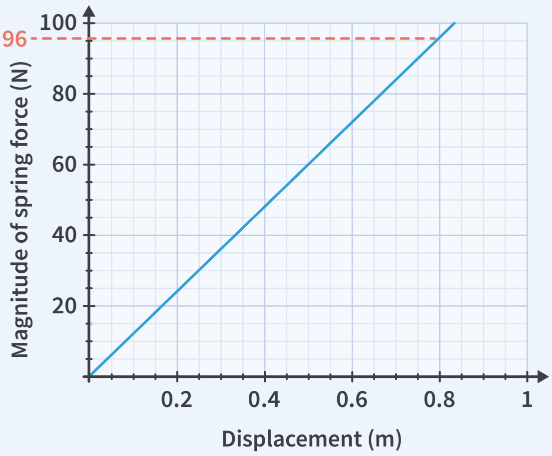
4 Substitute the formulas for the unknown energies:

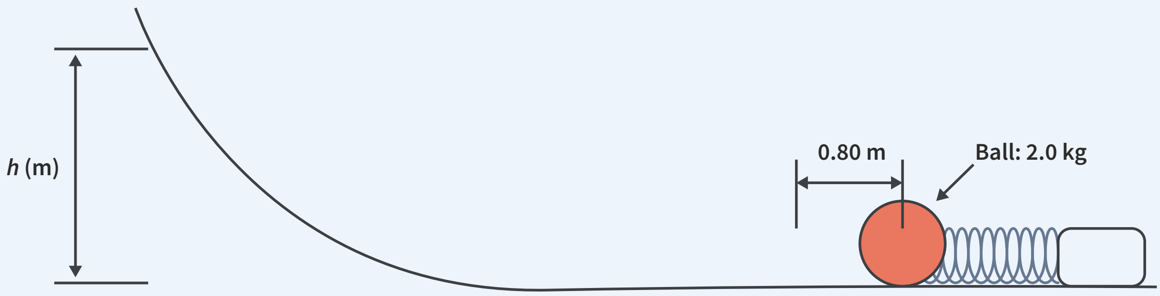
For example: $\frac{1}{2}k(\Delta x)_i^2 = \frac{1}{2}mv^2 + mgh_f$

5 Substitute the remaining values into the equation and solve.

2 Worked example

A compressed spring is used to launch a 2.0 kg ball on a horizontal surface. The ball then continues to roll up a ramp which is also frictionless. The spring is initially compressed by 0.80 m and its force-displacement characteristics are shown in the graph.





a **Use the graph to calculate the spring constant, *k*.**

b **Calculate the strain potential energy in the spring when it is initially compressed.**

c **Calculate the maximum speed of the ball.**

d **Calculate the maximum height that the ball reaches up the ramp.**

a The spring constant is found as the gradient of the force-displacement graph.

$k = gradient = \frac{rise}{run} = \frac{96-0}{0.8-0} = 120 \text{ N m}^{-1}$

b $SPE = \frac{1}{2}k(\Delta x)^2$

$SPE = \frac{1}{2} \times 120 \times 0.80^2 = 38.4 \text{ J}$

OR

Alternatively we can use the area under the graph:

$SPE = \frac{1}{2} \times \Delta x \times F_s = \frac{1}{2} \times 0.80 \times 96 = 38.4 \text{ J}$

c The ball is travelling fastest just after being released and before going up the ramp. Use energy conservation.
Initial state: ball at rest next to compressed spring.
Final state: ball rolling along horizontal surface with spring at natural length.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

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.

Just after the ball is released from the spring:

$GPE_f = 0$ as the ball is still at the lowest point.

$SPE_f = 0$ as the spring has returned to its natural length.

Ignoring the values that are zero, we will rewrite the energy statement as:

$SPE_i = KE_f$

Substitute the formulas for the unknown energies:

$\frac{1}{2}k(\Delta x)^2 = \frac{1}{2}mv^2$

Substitute the known values into the equation:

$\frac{1}{2} \times 120 \times 0.80^2 = \frac{1}{2} \times 2.0 \times v^2$

Rearrange and solve for v: $v = 6.2 \text{ m s}^{-1}$.

d Use energy conservation.
Initial state: ball at rest next to compressed spring (same as part **c**).
Final state: ball at its highest point on the ramp.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

At the highest point:

$KE_i = 0$ as the ball briefly stops when it reaches its maximum height.

$SPE_f = 0$ as the spring has returned to its natural length.

Ignoring the values that are zero, we will rewrite the energy statement as:

$SPE_i = GPE_f$

Substitute the formulas for the unknown energies: $\frac{1}{2}k(\Delta x)^2 = mgh$

Substitute the known values into the equation: $\frac{1}{2} \times 120 \times 0.80^2 = 2.0 \times 9.8 \times h$

Rearrange and solve for h: $h = 2.0$ m.

Theory summary

- Hooke's law relates the spring force to the displacement of a spring: $F_s = -k\Delta x$.
- When a block is hanging on a spring in equilibrium, $mg = k\Delta x$.
- Strain potential energy can be calculated by $SPE = \frac{1}{2}k(\Delta x)^2$
- On a force-displacement graph for an ideal spring
  - the graph is linear.
  - the gradient is equal to the spring constant, k.
  - the area under the graph is equal to the strain potential energy.
- Conservation of energy
  - Energy can be transformed between kinetic, gravitational and strain potential energy or dissipated as heat and sound but the total energy in a system must remain constant.
  - When no energy is dissipated: $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

KEEN TO INVESTIGATE?

oPhysics 'Conservation of Mechanical Energy: Mass on a Vertical Spring' simulation

https://ophysics.com/e1.html

PhET 'Masses and springs' simulation

https://phet.colorado.edu/en/simulation/masses-and-springs

3E Questions

THEORY REVIEW QUESTIONS

Question 1

Hooke's law is given by

A $SPE = \frac{1}{2}k(\Delta x)^2$

B $mg = -k\Delta x$

C $F_s = -k\Delta x$

D $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

Question 2

A spring is known to be ideal if

A it obeys Hooke's law.

B the spring constant, k, is equal to zero.

C the spring is positioned horizontally.

D the unstretched spring is greater than the length of the stretched spring.

Question 3

The shape of a force-displacement graph for an ideal spring is

A linear and horizontal.

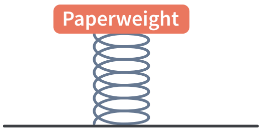
B linear and diagonal.

C exponential.

D hyperbolic.

Use the following information to answer Questions 4 and 5.

A spring is being compressed by a paperweight resting on top of it.



Question 4

If only the mass of the paperweight was known, which equation would best be used to calculate the magnitude of the spring's restoring force?

A $F_s = mg$

B $F_s = k\Delta x$

C $F_s = \frac{1}{2}k(\Delta x)^2$

D $F_s = mgk\Delta x$

Question 5

If the mass of the paperweight and the compression of the spring was known, which equation would we use to calculate the spring constant?

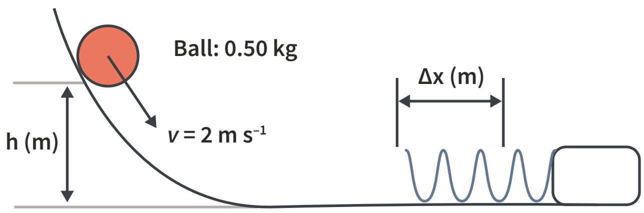
A $F_s = mg$

B $F_s = k\Delta x$

C $SPE = \frac{1}{2}k(\Delta x)^2$

D $mg = k\Delta x$

Question 6



Which forms of energy are relevant to the situation shown in the diagram as the ball rolls down the ramp and compresses the spring?

A *GPE* and *SPE*

B *GPE* and *KE*

C *KE* and *SPE*

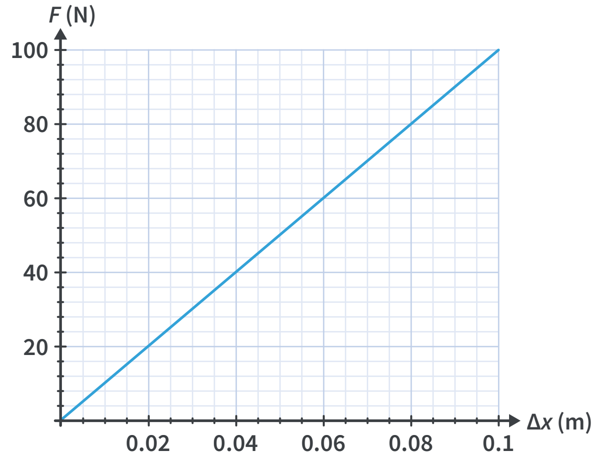
D *GPE*, *KE* and *SPE*

EXAM-STYLE QUESTIONS

This lesson

Question 7 (8 MARKS)

The force-displacement graph for an ideal spring is as shown.

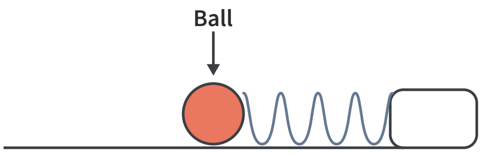


a Use the graph to determine the spring constant, k. (1 MARK)

b Given that a force of 40 N is applied to the spring, what is the magnitude of the compression, Δx, of the spring? Assume the spring is stationary. (1 MARK)

c Calculate the strain potential energy when a force of 40 N is applied to the spring. Assume the spring is stationary. (2 MARKS)

An initially stationary 3.0 kg ball is shot from the spring when it is allowed to expand from a compression of 0.080 m.



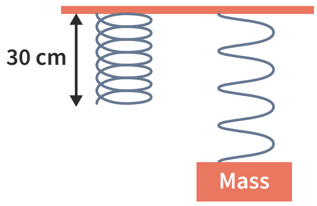
d Calculate the work done by the spring on the ball. Give appropriate units. (2 MARKS)

e Calculate the speed of the ball when it leaves the spring. Show the steps involved in your working out. (2 MARKS)

Adapted from 2017 VCAA Exam Section A Q12

Question 8 (4 MARKS)

A spring-mass system has been set up. The spring has an unstretched length of 30 cm.



In order to determine the spring constant, k, students progressively place 25 g masses onto an unstretched spring and measure the resultant length.

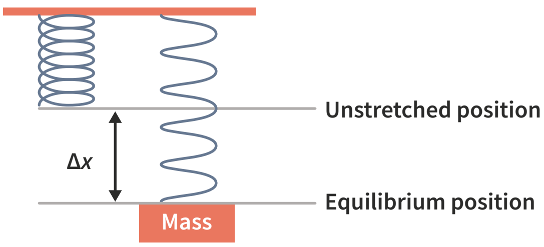
Number of masses	0	1	2	3
Length of spring	30 cm	40 cm	50 cm	60 cm

a Show that the spring constant is equal to 2.45 N m^{-1}. (2 MARKS)

b What is the strain potential energy when the spring is loaded with two masses? (2 MARKS)

Adapted from 2014 VCAA Exam Section A Q2

Question 9 (4 MARKS)



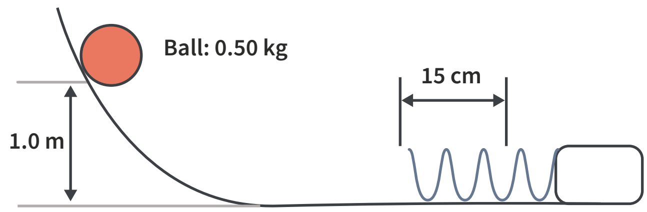
A 4.5 kg mass is suspended from a spring with a spring constant k = 350 N m^{-1}. Take the spring to be static.

a Calculate the extension of the spring from its unstretched position. Show your working out. (2 MARKS)

b Calculate the strain potential energy when the mass is at its equilibrium position. (2 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q5

Question 10 (5 MARKS)



A 0.50 kg ball is dropped down a ramp from a height of 1.0 m before compressing a horizontal spring by 15 cm from its uncompressed state.

a Show that $k = 4.4 \times 10^2$ N m^{-1}. (2 MARKS)

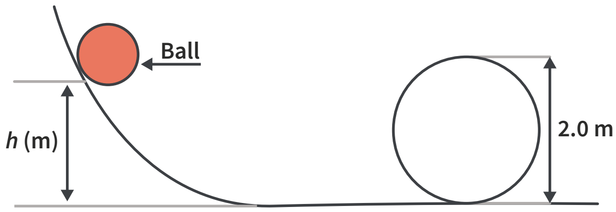
b If the ball is launched from the compressed spring, what is the maximum height that the ball reaches? (1 MARK)

c What is the maximum speed of the ball? (2 MARKS)

Previous lessons

Question 11 (5 MARKS)

Students roll a ball down a ramp onto a circular loop.



a Calculate the minimum speed at the top of the loop for the ball to maintain contact with the loop. (2 MARKS)

b What is the minimum height, h, that the ball can be dropped from in order to complete a loop? (3 MARKS)

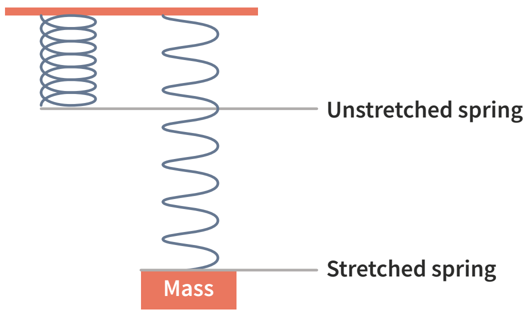
Question 12 (2 MARKS)

An ice hockey puck is travelling at 30 m s^{-1} and collides with a second puck. After the collision, the first puck comes to a complete stop. Given that both pucks have a mass of 1.5 kg, determine whether the collision was elastic. Justify your answer.

Key science skills

Question 13 (8 MARKS)

Students set up a test to determine the spring constant, k, of a spring.



Five 2.0 kg masses are incrementally attached to the end of the spring. The spring was slowly lowered to its equilibrium position. The resulting length of the spring was measured each time.

Number of 2.0 kg masses	0	1	2	3	4	5
Length of spring (m)	0.30	0.40	0.48	0.57	0.65	0.75

a Plot the data from the table onto a set of axes with mass on the horizontal axis and spring length on the vertical axis. Include axis labels, scales, and units on each axis. Given that the measurements were taken with a ruler that has 5 cm intervals and held by hand, insert realistic uncertainty bars (or error bars). Draw a line of best fit. (5 MARKS)

b Use your graph drawn in part **a** to determine the spring constant, k. (3 MARKS)

Adapted from 2017 VCAA Sample Exam Section B Q14

3F VERTICAL SPRING-MASS SYSTEMS

An oscillating spring is a common example of how various forms of energy can interact in a system, obeying the law of energy conservation. This lesson will examine the physics needed to understand the motion of vertical spring-mass systems. In particular, it will show how energy conservation can be applied to relate the different stages of motion in a spring-mass system.

3A Momentum and impulse	3B Kinetic energy, work and power	3C Elastic and inelastic collisions	3D Gravitational potential energy	3E Strain potential energy	3F Vertical spring-mass systems

Study design key knowledge dot point

- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

Key knowledge unit

Vertical spring-mass systems	3.3.15.3.3

Formulas for this lesson

Previous lessons		New formulas
2B	* $F_{net} = ma$	No new formulas in this lesson
2B	$F_g = mg$	
3B	* $KE = \frac{1}{2}mv^2$	
3D	* $\Delta GPE = mg\Delta h$	
3E	* $F_s = -k\Delta x$	
3E	* $SPE = \frac{1}{2}k(\Delta x)^2$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

equilibrium position (spring-mass system) the position of the mass at which the net force on the mass is zero. This position is always halfway between the two extreme points (endpoints) in oscillatory motion

oscillate move repetitively around a fixed position

spring-mass system the combination of a spring and a mass that is attached to one end of the spring

Vertical spring-mass systems 3.3.15.3.3

OVERVIEW

When a vertical spring stretches or compresses with the motion of an object, energy transforms between kinetic energy, gravitational potential energy, and strain potential energy. At the position where the spring has its maximum compression or extension, the object stops moving briefly. The forces are not balanced at this point. At the position where the forces are balanced, the object will move fastest.

THEORY DETAILS

Vertical spring-mass systems include both hanging springs and standing springs (see Figure 1). When a mass is **attached** to the vertical spring (rather than landing on the spring or being released from the spring), which is always the case for hanging springs, the mass will oscillate between a top and bottom position.

The force due to gravity on the mass does not change but the force of the spring changes in proportion to the displacement of the mass. Therefore, the net force, acceleration, and speed of the mass will also change.

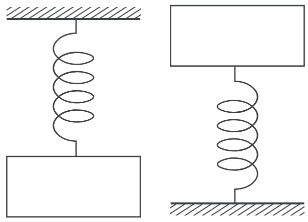


Figure 1 Vertical spring-mass systems include both hanging and standing springs.

Table 1 Comparison of acceleration and force with speed and kinetic energy at different points on a vertically oriented spring-mass system.

	Magnitude of acceleration and force	Speed and kinetic energy
Extreme positions (top/bottom)	Maximum The net force is a maximum	Zero The mass **momentarily** stops
Equilibrium position	Zero The net force is zero ($k\Delta x = mg$)	Maximum The mass has stopped accelerating and KE is a maximum

USEFUL TIP

When the mass is attached to the spring, the equilibrium position will be the midpoint between the top and bottom of the oscillation. This is also where the mass would eventually come to rest, given enough time, if energy is dissipated from the system.

For a vertical spring-mass system the equilibrium position is **not**

- the position of maximum extension or compression.
- the unstretched or uncompressed position.
- where strain potential energy is zero. If $\Delta x \neq 0$ then $SPE \neq 0$.

Energy conservation for a vertical spring-mass system

For a vertical oscillating spring there are three relevant forms of energy:

- Kinetic energy of the mass: KE
- Gravitational potential energy of the mass: GPE
- Strain potential energy of the spring: SPE
- Applying the law of energy conservation (and assuming energy is not dissipated from the system) we can conclude that the sum of these three energies must be the same at all stages of the motion: $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

USEFUL TIP

Equating spring force to the force on the mass due to gravity ($k\Delta x = mg$) applies to the equilibrium position. It does not determine the maximum extension of the oscillating spring.

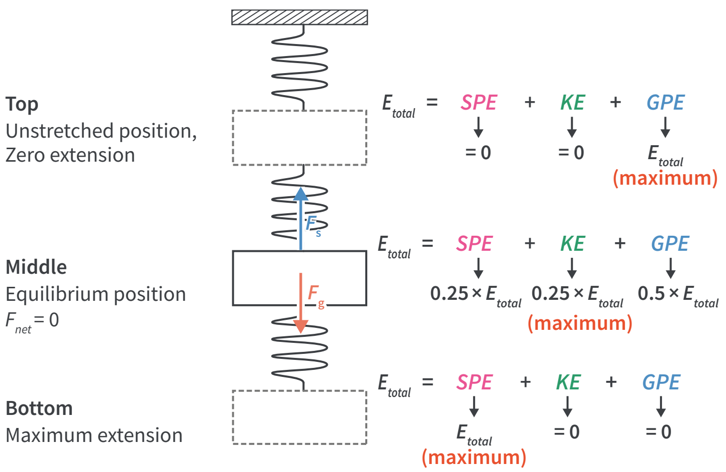


Figure 2 A mass released from the unstretched position of a hanging spring. The energy of the system transforms between strain potential energy, kinetic energy, and gravitational potential energy.

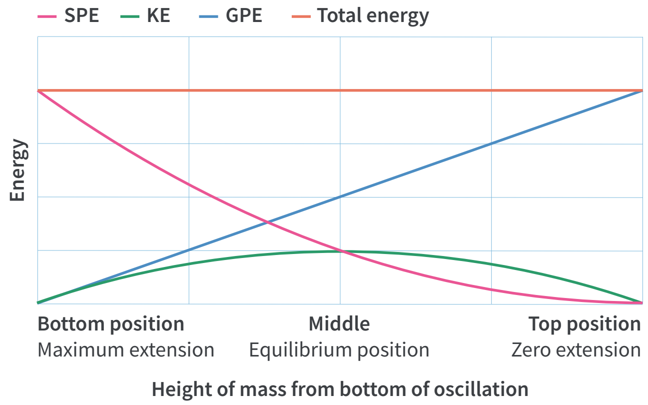


Figure 3 The strain potential energy, gravitational potential energy and kinetic energy of a hanging oscillating spring-mass system each vary with displacement, but the total energy is constant.

USEFUL TIP

The top position can be below or above the unstretched position in which case the strain potential energy in the top position will **not** be zero. This will depend on where the mass is released to begin the oscillation.

1 Worked example

A block of mass 0.050 kg is attached to the end of a hanging spring with a spring constant 10 N m^{-1}. The mass is initially held so that the spring is unstretched. It is then released. Calculate

a **the maximum extension of the spring.**

b **the extension of the spring at which the mass would come to rest.**

a Use energy conservation and define $h = 0$ at the lowest position.
Initial state: mass at the top in the unstretched position.
Final state: mass at the bottom of its oscillation.

$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

When the mass is at the top in the unstretched position:

$KE_i = 0$ as the mass starts from rest.

$SPE_i = 0$ as the spring starts from its natural/unstretched length.

When the mass is at the bottom of its oscillation:

$KE_f = 0$ as at the bottom of the oscillation the mass momentarily comes to rest.

$GPE_f = 0$ as the mass is at its lowest point.

Ignoring the values that are zero, we will rewrite the energy statement as:

$GPE_i = SPE_f$

Substitute the formulas for the unknown energies:

$mgh = \frac{1}{2}k(\Delta x)^2$

Substitute the known values into the equation:

$0.050 \times 9.8 \times h = \frac{1}{2} \times 10 \times (\Delta x)^2$

In this case $h = \Delta x$ because the top of the oscillation is at the unstretched position.

So we can rewrite the equation:

$0.050 \times 9.8 \times \Delta x = \frac{1}{2} \times 10 \times (\Delta x)^2$

Rearrange and solve for Δx: $\Delta x = 0.098$ m.

b The mass would come to rest at the equilibrium position, which is halfway between the top and the bottom of the oscillation and where $F_s = F_g$

As the equilibrium position is halfway between the maximum and minimum extension

$\textit{equilibrium position} = \frac{1}{2} \times 0.098$

$\textit{equilibrium position} = 0.049$ m

OR

$k\Delta x = mg$

$10 \times \Delta x = 0.050 \times 9.8$

$\Delta x = \frac{0.050 \times 9.8}{10} = 0.049$ m

Theory summary

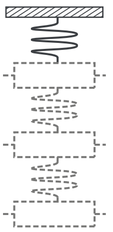
- Total energy must be conserved for an isolated vertical spring-mass system:
  - $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$
- At the top and bottom of an oscillation, the mass momentarily comes to a stop.
- In the equilibrium position, the mass is moving at its maximum speed (has maximum kinetic energy).
- The position of maximum compression or extension is **not** the equilibrium position.
- The equilibrium position is
  - halfway between the top and bottom positions of the oscillating spring.
  - where $k\Delta x = mg$.
  - where a mass will eventually come to rest over time, as energy is dissipated.

3F Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1 – 3.

The following diagram shows a block oscillating on a vertical hanging spring. The spring is at its natural length when the block is at the top of the oscillation (position X).



X Natural length, zero displacement

Y Equilibrium position

Z Maximum extension

Question 1

Which option correctly describes the energy forms at each of the three positions?

	Energy form	Position X	Position Y	Position Z
A	*KE* *GPE* *SPE*	Maximum Maximum Zero	Zero Medium Maximum	Maximum Minimum Zero
B	*KE* *GPE* *SPE*	Zero Maximum Maximum	Maximum Medium Zero	Zero Minimum Maximum
C	*KE* *GPE* *SPE*	Zero Maximum Zero	Maximum Medium Medium	Zero Minimum Maximum
D	*KE* *GPE* *SPE*	Zero Maximum Zero	Medium Medium Medium	Maximum Zero Maximum

Question 2

Which option correctly describes the magnitude of the net force at each of the three positions?

	Position X	Position Y	Position Z
A	Maximum	Medium	Zero
B	Maximum	Medium	Maximum
C	Maximum	Zero	Maximum
D	Zero	Zero	Zero

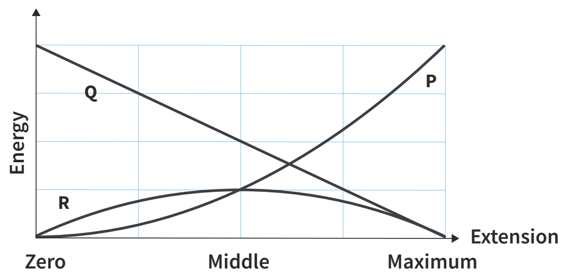
Question 3

Which option correctly describes the speed and magnitude of acceleration at each of the three positions?

		Speed	Acceleration magnitude
A	Position X Position Y Position Z	Zero Maximum Zero	Maximum Zero Maximum
B	Position X Position Y Position Z	Zero Medium Maximum	Constant (9.8 m s^{-2}) Constant (9.8 m s^{-2}) Constant (9.8 m s^{-2})
C	Position X Position Y Position Z	Zero Maximum Zero	Zero Maximum Zero
D	Position X Position Y Position Z	Zero Maximum Zero	Constant (9.8 m s^{-2}) Constant (9.8 m s^{-2}) Constant (9.8 m s^{-2})

Question 4

Below is the graph of each of the three relevant energy forms (labelled as P, Q and R) as a function of the distance of the block above its lowest point.



Which option correctly identifies the energy forms represented by P, Q and R?

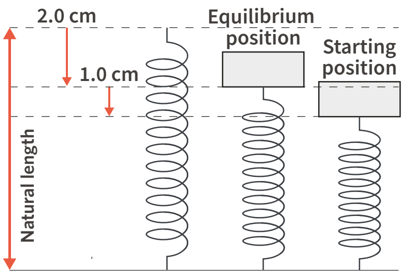
	Graph P	Graph Q	Graph R
A	*KE*	*GPE*	*SPE*
B	*GPE*	*SPE*	*KE*
C	*SPE*	*KE*	*GPE*
D	*SPE*	*GPE*	*KE*

EXAM-STYLE QUESTIONS

This lesson

Question 5 (3 MARKS)

Yokabit, Valeriy, and JL are conducting an experiment with a mass attached to a standing spring. When at rest, the mass compresses the spring by 2.0 cm. They intend to compress the spring by a further 1.0 cm (total compression of 3.0 cm) and measure the maximum height that the mass reaches when it oscillates.



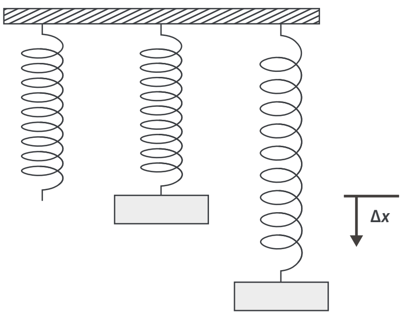
Each of the students has a different suggestion for the maximum height that the mass will reach:

- Yokabit suggests that the highest position will be the equilibrium position because the net force would act downwards if the mass was any higher;
- Valeriy suggests that the highest position will be the position at which the spring is uncompressed because the spring force would act downwards on the mass if the mass was any higher;
- JL suggests that the highest position will be 3.0 cm above the natural length (uncompressed position) because energy conservation suggests that the highest and lowest positions should be the same distance from the uncompressed position.

Evaluate each of these students' suggestions with supporting explanations. Ensure that you clearly state the correct height that the mass will reach in your answer.

Question 6 (10 MARKS)

Ryle and Rushil hang a mass of 0.800 kg on the end of a spring with spring constant 12 N m^{-1}. They initially hold the mass at the unstretched length of the spring and then release it.



a Determine how far the spring stretches until the mass comes to rest, before moving upwards again. (3 MARKS)

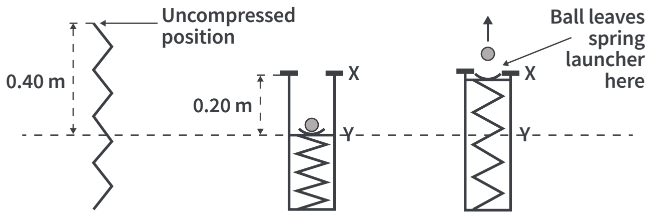
b Calculate the maximum speed of the mass. (3 MARKS)

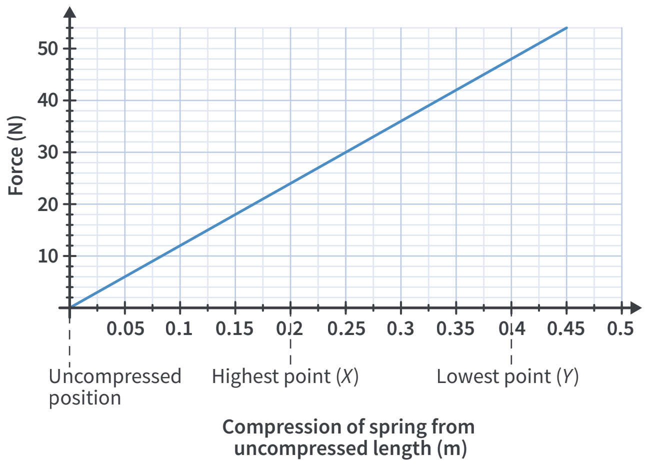
c Draw a graph showing the acceleration of the mass as it moves from the highest point to the lowest point, where upwards is the positive direction. The acceleration should be shown on the vertical axis and the extension of the spring should be shown on the horizontal axis. Include units and an appropriate scale on your graph. (3 MARKS)

d Using the same spring and mass, Ryle and Rushil now hold the mass at rest such that the spring has an initial extension of 30 cm. It is then released. Calculate the maximum extension of the spring. (1 MARK)

Question 7 (13 MARKS)

A spring launcher is used to project a 0.50 kg ball vertically upwards. When the spring reaches the top point X it is held stationary, but still partly compressed. Assume the spring has no mass.





a Use the graph to show that the spring constant k, is 120 N m^{-1}. (1 MARK)

b Show that the change in strain potential energy as the spring goes from its lowest to its highest point is 7.2 J. (2 MARKS)

c Assuming the change in strain potential energy is 7.2 J, determine the maximum height above the lowest point (Y) that the ball reaches after being launched. (3 MARKS)

d What is the speed of the ball at point X. (3 MARKS)

e Describe how the three energies and the total energy of the mass-spring system changes as the ball is launched from the lowest point Y to the highest point X. (4 MARKS)

Adapted from 2018 VCAA NHT Exam Section B Q9

Question 8 (3 MARKS)

Students design a vertically oscillating spring-mass system. They set up the system so that the mass is released from 20 cm below the unstretched spring length. They assume that

- at the point of release, the system has zero strain potential energy and zero kinetic energy;
- at the bottom of the oscillation, the system has zero gravitational potential energy and zero kinetic energy.

However their calculations for total energy (*KE* + *GPE* + *SPE*) give different values when comparing these two positions. Explain the mistake that the students have made.

Adapted from 2013 VCAA Exam Section A Q6c

Previous lessons

Question 9 (3 MARKS)

A ball is launched towards a wall which is 25 m away. The ball is launched from a height of 2.0 m at a speed of 20 m s^{-1} and angle of 40° above the horizontal. At what height above the ground will the ball hit the wall?

Question 10 (4 MARKS)

An aerobatics pilot with a mass of 60.0 kg completes a loop de loop in her plane which has a mass of 1000 kg. At the top of the loop she has a speed of 80.0 m s^{-1} and there is no normal force acting on her. At the bottom of the loop she is travelling at 100 m s^{-1}. Assuming that the loop is a perfect circle, calculate the magnitude of the normal force acting on her at the bottom of the loop.

Key science skills

Question 11 (4 MARKS)

Tommy and Arden are conducting an experiment in which they attach a 500 g mass to an unstretched hanging spring, and release the mass to measure the maximum extension of the spring during oscillation for a variety of springs with different spring constants.

They are making their measurements using a ruler which has markings at 5.0 cm increments.

a What is the uncertainty in the measured data as a result of the ruler which was used? (1 MARK)

b Identify the independent variable, dependent variable and a controlled variable for this experiment. (3 MARKS)

CHAPTER 3 QUESTIONS

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 car is moving towards a pedestrian crossing with a momentum of 10 800 kg m s^{-1}. The driver sees a pedestrian and has to suddenly brake. The car's momentum is reduced to 500 kg m s^{-1} over 0.250 s. What is the magnitude of the braking force applied to the vehicle?

A 41.2 kN **B** −41.2 kN **C** −10.3 kN **D** 10.3 kN

Use the following information to answer Questions 2–4.

A block of 15 kg moving at 50 m s^{-1} to the right collides with a block of 40 kg moving at 4.0 m s^{-1} to the left. After the collision they stick together. Assume there are no frictional forces.

Question 2

What is the magnitude of the combined momentum that the blocks have before the collision?

A 160 kg m s^{-1} **B** 590 kg m s^{-1} **C** 750 kg m s^{-1} **D** 910 kg m s^{-1}

Question 3

What is the velocity of the blocks after the collision?

A 2.9 m s^{-1} in the leftward direction

B 11 m s^{-1} in the rightward direction

C 14 m s^{-1} in the rightward direction

D 17 m s^{-1} in the rightward direction

Question 4

Which of the following statements is true?

A Momentum is conserved but kinetic energy is not conserved in the collision.

B Momentum is not conserved but kinetic energy is conserved in the collision.

C Both momentum and kinetic energy are conserved in the collision.

D Neither momentum or kinetic energy are conserved in the collision.

Question 5

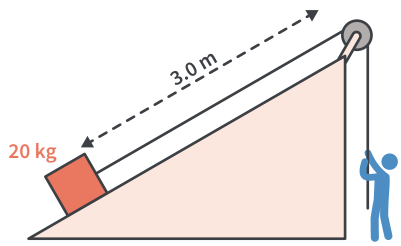
A worker pulls a 20 kg block up a distance of 3.0 m a ramp using a force of 100 N. How much work does the worker do on the block?

A 60 J

B 5.9×10^2 N m s^{-1}

C 3.0×10^2 J

D 5.9×10^2 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)

In a crash test for the Batmobile, Alfred (who happens to be an excellent mechanical engineer as well as a butler) crashed the test model into a solid stone wall. The car's mass is 1200 kg. It was travelling at a speed of 90 km h^{-1} and stopped in 0.10 seconds. Calculate the average force on the Batmobile.

Question 7 (2 MARKS)

A crumple zone is a region in a car which is designed to extend the duration of the collision by crumpling in the case of an accident. With reference to impulse, explain why crumple zones are an effective safety mechanism.

Question 8 (2 MARKS)

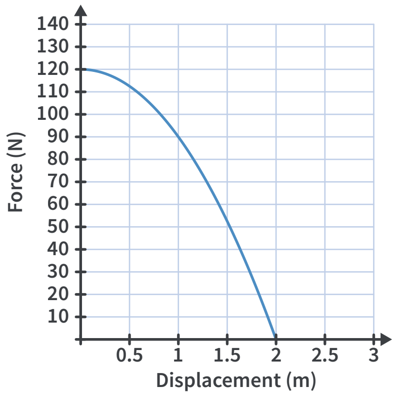
A PE teacher is holding up a heavy object above her head. She states that she is doing a lot of work to hold the object above there. Evaluate this statement and justify your answer.

Question 9 (5 MARKS)

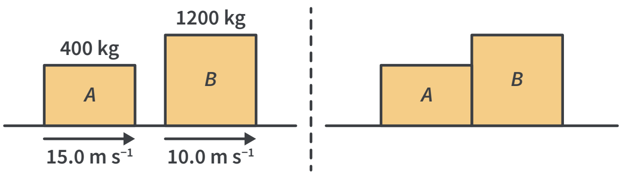
The graph shows the force that a baseball pitcher applies in a horizontal direction to a 150 g baseball over a distance of 2.0 m. The ball starts from rest.

a What is the work done by the pitcher on the baseball? (3 MARKS)

b What is the speed of the ball as it leaves the pitcher's hand? (2 MARKS)



Question 10 (4 MARKS)



Two blocks are travelling to the right on a frictionless surface. Block *A* has a speed of 15.0 m s^{-1} and block *B* has a speed of 10.0 m s^{-1}. After they collide, the masses attach together. Using calculations, determine whether the collision is elastic or inelastic.

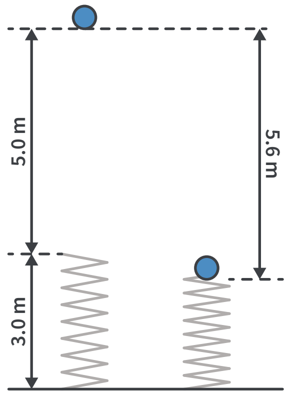
Adapted from 2017 VCAA Exam Section B Q12

Question 11 (3 MARKS)

A football with a mass of 0.50 kg is thrown downwards with an initial kinetic energy of 6.25 J from the Sydney Harbour Bridge. The ball impacts the water with a speed of 31 m s^{-1}. Calculate the height of the bridge. Ignore the effects of resistance forces.

Question 12 (8 MARKS)

A ball of 1.5 kg is dropped from a height of 5.0 m above an uncompressed spring 3.0 m tall. The ball comes to rest 5.6 m below its original position. Take the spring constant to be $k = 457$ N m^{-1}.



a What is the spring potential energy when the ball has come to a complete stop? (2 MARKS)

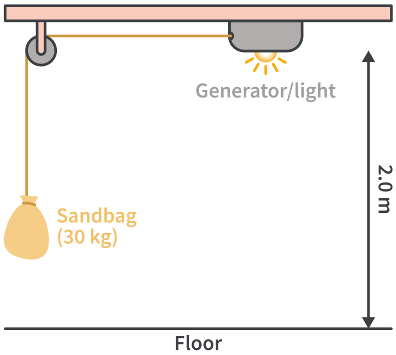
b How far has the spring been compressed when the ball reaches its maximum speed? (3 MARKS)

c The spring is replaced by a different one with a spring constant of 200 N m^{-1}. For this new spring, the ball is again dropped from a height 5.0 m above the spring, and it reaches its maximum speed when the spring is compressed by 7.35×10^{-2} m. Find the maximum kinetic energy of the ball. (3 MARKS)

Adapted from 2018 VCAA Exam Section B Q6

Question 13 (4 MARKS)

Engineers set up a gravity light as shown. The energy from a falling sandbag with a mass of 30 kg is used via an electrical generator to power an LED light. The LED light uses 1.5 J s^{-1}. The maximum height of the sandbag is 2.0 m from the floor. Assume the generator is ideal, meaning it converts all the input energy to light energy.

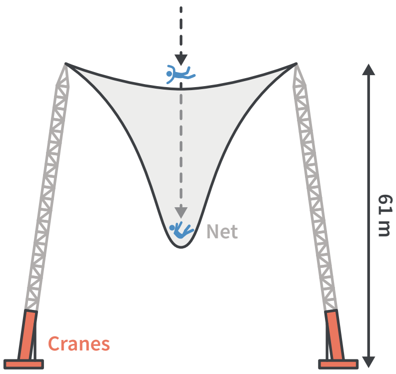


a How much energy can the sandbag deliver to the LED by falling from the maximum height to the ground? Ignore resistance forces and assume the kinetic energy of the bag when it reaches the ground is negligible. (2 MARKS)

b For how much time will the LED stay on as a result of the sandbag falling from the maximum height to the ground? (2 MARKS)

Question 14 (8 MARKS)

In 2016, Luke Aikins (70.0 kg) skydived out of a plane at 7661 m without a parachute. Due to air resistance, Aikins reached a terminal (maximum) velocity of 240 km h^{-1}. He opted to land in an enormous net with an area of 30 m by 30 m. Assume that the net follows Hooke's law. The net was set up on 61 m tall cranes and it was initially flat before Aikins landed on the net.



a How much of Aikins' initial gravitational potential energy was dissipated to air resistance in his skydive by the time he hit the top of the net? (3 MARKS)

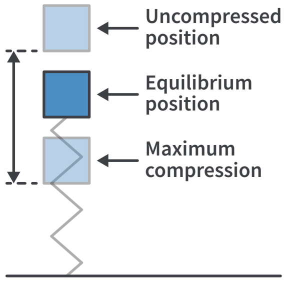
b What must the minimum spring constant of the net be so that Aikins does not hit the ground? (3 MARKS)

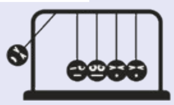
c Calculate the magnitude of the impulse on Aikins between when he first lands on the net and when he comes to rest. (2 MARKS)

Question 15 (7 MARKS)

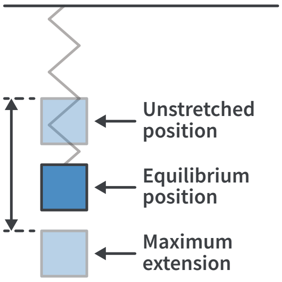
A mass is attached to a standing spring at its unstretched length and released, allowing it to oscillate.

a Explain how the three energies involved, and the total energy of the system, vary as the mass descends from top to bottom. Calculations are not required. (4 MARKS)





b A different spring is hung from the roof with a 4.8 kg mass attached. It is released from the unstretched position and allowed to oscillate. The spring constant is 50 N m^{-1}. Calculate the magnitude of the maximum extension of the spring. (3 MARKS)



Adapted from 2017 VCAA Exam Section B Q13

UNIT 3 AOS 3, CHAPTER 4

Einstein's special relativity and mass-energy equivalence

04

Key knowledge

- describe Einstein's two postulates for his theory of special relativity that:
  - the laws of physics are the same in all inertial (non-accelerated) frames of reference
  - the speed of light has a constant value for all observers regardless of their motion or the motion of the source
- compare Einstein's theory of special relativity with the principles of classical physics
- describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- model mathematically time dilation and length contraction at speeds approaching c using the equations: $t = t_0\gamma$ and $L = \frac{L_0}{\gamma}$ where $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}$
- explain why muons can reach Earth even though their half-lives would suggest that they should decay in the outer atmosphere
- interpret Einstein's prediction by showing that the total 'mass-energy' of an object is given by: $E_{tot} = E_k + E_0 = \gamma mc^2$ where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = (\gamma - 1)mc^2$
- describe how matter is converted to energy by nuclear fusion in the Sun, which leads to its mass decreasing and the emission of electromagnetic radiation

4A SPECIAL RELATIVITY CONCEPTS

This lesson will lay down the foundations for understanding Einstein's theory of special relativity which applies to relative motion at a constant speed in a straight line. We will learn Einstein's two postulates, which have implications for our understanding of space and time. The outcomes of special relativity will be contrasted with our intuitive understanding of classical physics.

4A Special relativity concepts	4B Length contraction and time dilation	4C Mass-energy

Study design key knowledge dot points

- describe Einstein's two postulates for his theory of special relativity that:
  - the laws of physics are the same in all inertial (non-accelerated) frames of reference
  - the speed of light has a constant value for all observers regardless of their motion or the motion of the source
- compare Einstein's theory of special relativity with the principles of classical physics

Key knowledge units

Einstein's first postulate	3.3.7.1
Einstein's second postulate	3.3.7.2
Comparing special relativity with classical physics	3.3.8.1

Formulas for this lesson

Previous lessons		New formulas
2A	* $v = \frac{\Delta s}{\Delta t}$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

frame of reference a set of coordinates by which we measure the relative location and motion of objects

inertial frame of reference a non-accelerating frame of reference

Einstein's first postulate 3.3.7.1

OVERVIEW

A frame of reference is like a perspective from which we measure the relative location and motion of objects. An **inertial** frame of reference is one which is moving at a constant velocity (not accelerating). Einstein's first postulate states that the laws of physics are the same for all inertial frames of reference.

THEORY DETAILS

Frames of references

A frame of reference is a set of coordinates by which we measure the relative location and motion of other objects. Every object can be said to be at the origin (centre) of its own frame of reference which means the relative location and motion of other objects will depend on the reference frame in which the measurements are made.

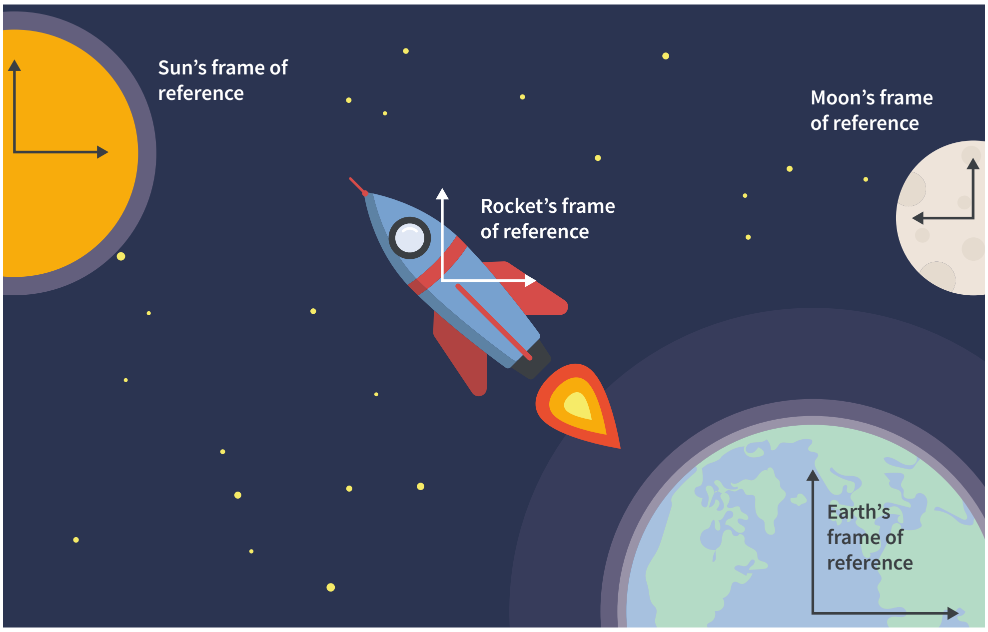


Figure 1 Different frames of reference in our solar system. Each set of axes represents the individual reference frames for each object. The diagram is not drawn to scale!

As an example, consider the driver and the passenger in the rear seat of a car in Figure 2.

- In the passenger's reference frame, the driver is not moving: she is a fixed distance of one metre in front.
- In the pedestrian's reference frame, both the driver and the passenger are travelling at 10 m s^{-1}.

Both measurements are correct. They indicate that all motion is relative: it is meaningful only when it is described in relation to something else.

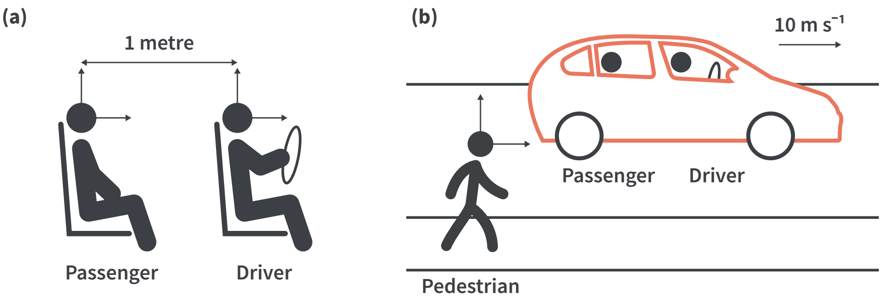


Figure 2 From the passenger's frame of reference **(a)** the driver is not moving but from a pedestrian's frame of reference **(b)** both the driver and passenger are moving at 10 m s^{-1}

Inertial (non-accelerating) frames of reference

An inertial frame of reference is one which is not accelerating (has a constant velocity). Examples of inertial frames of reference include:

- your frame of reference when you are sitting still.
- a car's frame of reference when it is travelling at a constant speed in a constant direction.
- an aeroplane's frame of reference while it is flying north at a constant speed of 900 km h^{-1}.

Examples of non-inertial frames of reference include:

- your frame of reference as you speed up from a walk to a run.
- a car's frame of reference when it is travelling at a constant speed around a corner.
- an aeroplane's frame of reference while it is speeding up for take-off or slowing down as it lands on the runway.

Note that, due to the Earth's rotation, a reference frame which is at rest on the surface of the Earth is not strictly considered an inertial frame of reference. However, the effects of this rotation are small. For the purposes of VCE Physics and our discussion in this book, we will treat reference frames on the surface of the Earth as inertial reference frames.

USEFUL TIP

Constant speed is not a sufficient condition to describe an inertial frame of reference. Constant velocity (speed and direction) is required for an inertial frame of reference.

Einstein's first postulate

A postulate is an assumed fact. **Einstein's first postulate** states that the laws of physics are the same in all inertial frames of reference.

- In an inertial reference frame, the results of all experiments will be the same. This means that there is no absolute (uniquely correct) frame of reference in which we should measure velocity.
- In an accelerating reference frame, the results of an experiment will depend on the acceleration.

Imagine sitting on an aeroplane with ears blocked (so we cannot hear the engine) and the windows shut. There is no way of knowing whether the aeroplane is stationary at the airport or flying at 900 km h^{-1} in a constant direction. If we drop a ball in the aeroplane we will measure it to fall vertically at the same rate in either situation, as long as we take our measurements in each situation from the aeroplane's frame of reference. This is the meaning of Einstein's first postulate. By contrast, if we drop a ball while the aeroplane is accelerating for take-off, the ball will fall towards the back of the aeroplane. Similarly, when the aeroplane turns the associated acceleration will change the results of this ball-drop experiment.

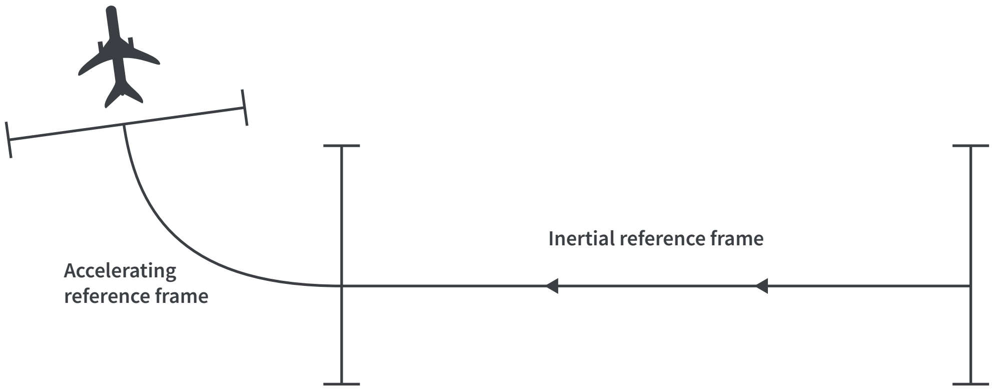


Figure 3 An aeroplane viewed from above. When moving in a constant direction with a constant speed, the aeroplane is in an inertial frame of reference. As soon as the speed or direction changes (acceleration occurs), it is no longer in an inertial frame of reference.

Note that, so far, we have not made any claims that disagree with classical physics. That is, Einstein's first postulate, by itself, agrees with classical physics.

Einstein's second postulate 3.3.7.2

OVERVIEW

Einstein's second postulate states that all inertial frames of reference will measure light to travel at the same speed in a vacuum, *c*, which has the value 3.0×10^8 m s^{-1} when measured to two significant figures.

THEORY DETAILS

As discussed earlier, the speed of most objects (such as the driver in Figure 2) is a relative measurement: different reference frames will measure different speeds. The exception to this is light (and other massless particles, but in the VCE Physics course we will focus on light).

Einstein's second postulate states that the speed of light in a vacuum (*c*) is the same for all observers, regardless of the motion of the observer or the light source. That speed is 3.0×10^8 m s^{-1} to two significant figures. This postulate is supported by the Michelson-Morely experiment (which is not expected knowledge in VCE physics).

As seen in Figure 4(a), the passenger (and the driver) measures light from a torch to travel at *c* in the passenger's reference frame, but the pedestrian also measures the light to travel at *c* in the pedestrian's reference frame, which is shown in Figure 4(b).

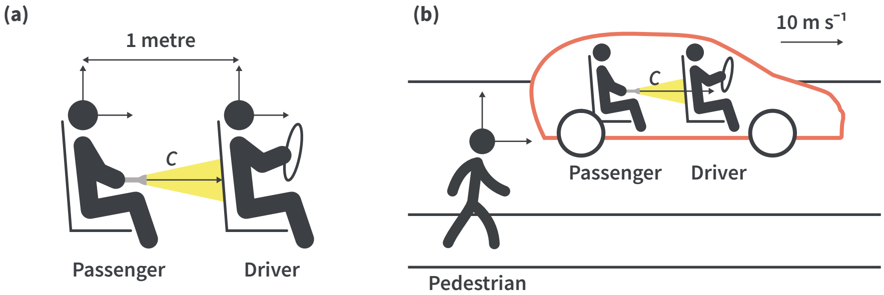


Figure 4 The speed of light in a vacuum is c for all observers regardless of the relative motion of the observer and the source of light.

Comparing special relativity with classical physics 3.3.8.1

OVERVIEW

The conclusion of Einstein's postulates is the theory of special relativity which challenges our intuitive understanding of space and time, and predicts different results to those predicted by classical physics. According to special relativity, space and time are not absolute: space is measured to contract and time is measured to dilate such that the speed of light has the same value when measured by any frame of reference. Table 1 summarises the important comparisons we need to make in VCE Physics.

THEORY DETAILS

Space and time

Classical physics assumes that space and time are absolute which means that observers in different reference frames should always agree about their measurements of length and time. At low relative speeds these assumptions are good approximations, but they are only approximations. At very high speeds ('relativistic speeds') classical physics predicts results which differ significantly from accurate measurements.

As with any speed, the speed of light is a measure of the rate of change of distance with respect to time ($c = \frac{\Delta s}{\Delta t}$). In order for all observers to measure the same speed of light (as described by Einstein's second postulate), space (in terms of length, Δs) and time (Δt) must change depending on an observer's reference frame. These changes, known as **length contraction** and **time dilation**, will be applied in lesson 4B and they underpin Einstein's theory of special relativity. The predictions of the theory of special relativity, so far, have been supported by experimental measurements for uniform motion at all speeds.

Relative speeds

Figure 5 shows two rockets travelling towards each other each at 60% of the speed of light ($0.60c$) as measured from the Earth's frame of reference. According to classical physics, Rocket 1 should measure Rocket 2's relative speed to be $0.60c + 0.60c = 1.20c$.
In reality, the relative speed will be $0.88c$. The details of this are beyond the scope of VCE Physics, but it is important to understand that the difference exists. The theory of special relativity can explain this difference as a result of the different length and time measurements taken from Rocket 1's frame of reference compared to the Earth's frame of reference.

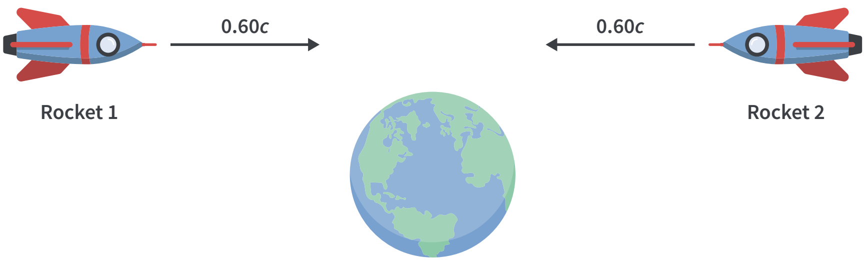


Figure 5 Two rockets are directed towards each other at $0.60c$ as measured in Earth's frame of reference. The relative speed of the rockets cannot be accurately calculated using classical physics principles.

Lesson 4C will explain why objects with mass can never reach the speed of light and how kinetic energy approaches infinity as an object approaches the speed of light.

Table 1 A summary of the comparison between the principles of classical physics and special relativity

	Classical physics prediction	Special relativity prediction
Space and time	Fixed – all observers agree on measurements of length and time	Flexible – length and time measurements change between reference frames
Relative speeds	Additive – all values of relative speed are possible	Not additive – the relative speed of objects with mass can never reach the speed of light
Kinetic energy	Increases in proportion to v^2 and has a finite value for every speed.	Requires a different formula (covered in lesson 4C) and approaches infinity as speed approaches c.

Theory summary

- An inertial frame of reference is a non-accelerating set of coordinates from which measurements can be made.
- Einstein's first postulate states that the laws of physics are the same for all inertial frames of reference.
  - It is impossible for an observer to determine their velocity without referring to the external world.
- Einstein's second postulate states that the speed of light is the same for all observers regardless of their motion or the motion of the source of the light.
- Special relativity makes different predictions to classical physics.
  - Space and time are not absolute.
  - Relative speeds are not additive and cannot exceed c.
  - Kinetic energy approaches infinity as the speed of an object approaches c.

KEEN TO INVESTIGATE?

YouTube video: Fermilab – Why can't you go faster than light?
https://youtu.be/A2JCoIGyGxc

YouTube video: Frame of Essence – SR1: The Light that will Light the Spark - The Michelson-Morley Experiment
https://youtu.be/uMaFB3jM2qs

YouTube video: PBS Space Time – The Speed of Light is NOT About Light
https://youtu.be/msVuCEs8Ydo

YouTube video: Physics Girl – Special Relativity and the Twin Paradox
https://youtu.be/ERgwVm9qWKA

YouTube video: Professor Dave Explains – Relative Motion and Inertial Reference Frames
https://youtu.be/wD7C4V9smG4

YouTube video: Trev M – Frames of Reference (1960)
https://youtu.be/bJMYoj4hHqU

4A Questions

THEORY REVIEW QUESTIONS

Question 1

The best description of Einstein's first postulate is that

A the laws of physics are the same for all frames of reference.

B the laws of physics are the same for all inertial frames of reference.

C the classical laws of physics are the same for all frames of reference.

D the classical laws of physics are the same for all inertial frames of reference.

Question 2

The best description of Einstein's second postulate is that

A the speed of all waves is the same for all frames of reference.

B the speed of light in a vacuum is the same for all stationary observers.

C the speed of light in a vacuum is the same for all observers.

D the speed of light in a vacuum depends on the motion of the source of light.

Question 3

An inertial frame of reference can best be explained as

A a set of coordinates from which the location of other objects is measured.

B a set of coordinates from which the relative location and motion of objects can be measured.

C a set of coordinates with a constant velocity from which the relative location and motion of objects can be measured.

D a set of coordinates with a changing velocity from which the relative location and motion of objects can be measured.

Question 4

A car is travelling in a straight line at a constant speed of 30 km h^{-1} relative to a pedestrian who is walking at 5 km h^{-1} in the same direction. What is the **absolute speed** of the car?

A 30 km h^{-1}

B 35 km h^{-1}

C 50 km h^{-1}

D There is no absolute speed. Speed is relative.

Question 5

Choose whether each statement agrees with the principles of **classical physics**, **special relativity**, or **both**.

S1 The laws of physics are the same in all inertial reference frames.

S2 Space and time are fixed. All observers make the same measurements of length and time.

S3 Relative speeds cannot exceed *c*.

S4 Speed is relative. There is no absolute speed.

S5 Space and time are flexible. Measurements of length and time change between reference frames.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

Which of the following is not in an inertial frame of reference?

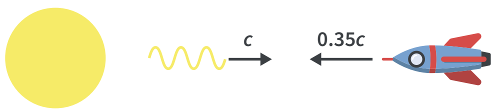
A A rocket in deep space travelling in a straight line at a constant speed of 0.8*c*.

B A car moving at a constant speed whilst turning a corner.

C An observer standing still on the ground.

D An aeroplane flying at a constant speed 970 km h^{-1} in a straight line.

Question 7 (1 MARK)



Light emitted from the Sun travels towards a spacecraft at speed *c*. That spacecraft is travelling at a constant speed towards the Sun at 0.35*c*, when measured in the Sun's frame of reference. At what speed will an observer on the spacecraft measure the light to travel?

A 0.35*c*

B 0.65*c*

C *c*

D 1.35*c*

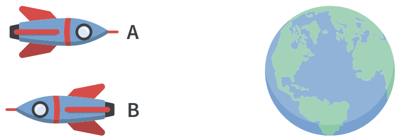
Question 8 (3 MARKS)

Anna believes that any object moving at a constant speed is in an inertial frame of reference. Is she correct? Justify your answer.

Adapted from 2018 VCAA Exam Section B Q14

Question 9 (3 MARKS)

In deep space, a spaceship, A, is travelling towards the Earth when it passes a second spaceship, B, travelling in the opposite direction with a relative speed of 0.8*c*. At this instant, each spaceship sends a light pulse back towards the Earth which is the same distance from each spaceship.



a Which of the following statements about the arrival time of the light pulse at the Earth is true? (1 MARK)

A The light pulse from A arrives before the light pulse from B.

B The light pulse from B arrives before the light pulse from A.

C The order of the light pulses arriving at the Earth depends on which reference frame is taking the measurements.

D Both light pulses arrive at the same time.

Adapted from 2011 VCAA Exam 1 Section B Detailed study 1 Q5

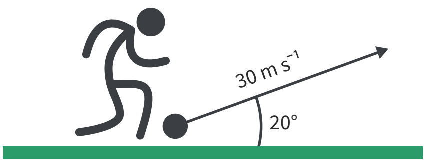
b Given that the spaceships are 6.0×10^{11} m from the Earth (as measured by an observer on Earth) when they send the light pulses, calculate how long the light pulse from spaceship A takes to reach the Earth as measured by an observer on Earth. Give your answer in seconds. (2 MARKS)

Adapted from 2010 VCAA Exam 1 Section B Detailed study 1 Q1

Previous lessons

Question 10 (5 MARKS)

A stick figure kicks a soccer ball at 30 m s^{-1} at a 20° angle above the horizontal. Ignore the effects of air resistance in this question.



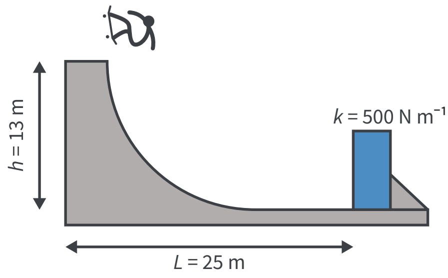
a What is the vertical component of the soccer ball's velocity? (1 MARK)

b Find the maximum height that the soccer ball reaches. (2 MARKS)

c Calculate the time from when the ball leaves the ground to when it returns to the ground. (2 MARKS)

Question 11 (4 MARKS)

A skateboarder with a mass of 67 kg skates down a ramp that is 13 m tall and 25 m long as shown in the diagram. The skateboarder is brought to rest by a crash mat, which provides a force on the skateboarder as it compresses according to Hooke's law. The mat has a spring constant of 500 N m^{-1}.



a What is the maximum speed of the skateboarder? (2 MARKS)

b Calculate the maximum compression of the mat. (2 MARKS)

Key science skills

Question 12 (2 MARKS)

Emma conducts an experiment to measure the time it takes a ball, which starts with a known initial speed, to roll **a distance of 10 metres**. To do this, she:

- marks two parallel lines (a start line and a finish line) which are 10 metres apart on the floor of a train carriage;
- releases the ball with the known initial speed from the start line;
- measures the time until the ball crosses the finish line.

The train is travelling along a **curved track** at the time of the experiment. Comment on the validity of Emma's experimental procedure.

4B LENGTH CONTRACTION AND TIME DILATION

In the previous lesson we learned Einstein's two postulates and how they imply that space and time will change depending on an observer's frame of reference. In this lesson we will learn the formulas that quantify length contraction and time dilation through the use of the Lorentz factor.

4A Special relativity concepts	4B Length contraction and time dilation	4C Mass-energy

Study design key knowledge dot points

- describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- model mathematically time dilation and length contraction at speeds approaching c using the equations: $t = t_0\gamma$ and $L = \frac{L_0}{\gamma}$ where $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$
- explain why muons can reach Earth even though their half-lives would suggest that they should decay in the outer atmosphere

Key knowledge units

The Lorentz factor (γ)	3.3.11.1
Length contraction	3.3.10.1 & 3.3.11.3
Time dilation	3.3.9.1 & 3.3.11.2
Muon detection as evidence for special relativity	3.3.12.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
	* $t = t_0\gamma$
	* $L = \frac{L_0}{\gamma}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

contracted length the length of an object measured in a reference frame where the object is moving; this length is always shorter than the proper length

dilated time the time interval between two events measured in a reference frame where the two events occur at different points in space; this time is always greater than the proper time between the events

event something that occurs at a particular location and time

proper length the length of an object measured in a reference frame where the object is at rest

proper time the time interval between two events measured in a reference frame where the two events occur at the same point in space

rest length see proper length

The Lorentz factor (γ) 3.3.11.1

OVERVIEW

The Lorentz factor is a dimensionless quantity which determines the magnitude of relativistic effects, including time dilation and length contraction.

THEORY DETAILS

Relativistic speeds

Relativistic speeds are speeds where the effects of special relativity become significant. These speeds are often written as a multiple of *c* (the speed of light). To convert from metres per second to a multiple of *c*, the value must be divided by 3.0×10^8. For an object moving at 1.5×10^8 m s^{-1}, its speed can also be written as $\frac{1.5 \times 10^8}{3.0 \times 10^8} = 0.5c$.

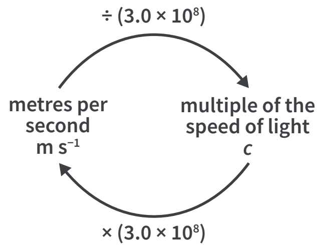


Figure 1 Diagram showing the operations required to convert metres per second into a multiple of the speed of light and vice versa

The Lorentz factor

The Lorentz factor is a property of the relative speed between frames of reference and it determines the magnitude of length contraction or time dilation. An object that is measured in a given reference frame to be at rest has a Lorentz factor of one, meaning there is no length contraction or time dilation observed. It is calculated from the following formula.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

γ = Lorentz factor (no units), v = velocity (m s^{-1}), c = speed of light (3.0×10^8 m s^{-1})

Rearranging this formula, the relative speed can be calculated from a known value of the Lorentz factor using $v = c\sqrt{1 - \frac{1}{\gamma^2}}$.

As the relative speed approaches the speed of light, the Lorentz factor approaches infinity (the speed of light acts as a vertical asymptote).

For speeds we experience in everyday life the Lorentz factor is extremely close to one, so there are no observable changes in space and time in our frames of reference.

Table 1 A table of values which shows the Lorentz factor for different speeds.

Relative speed	Lorentz factor (γ)
0	1.000
0.5*c*	1.155
0.6*c*	1.250
0.7*c*	1.400
0.8*c*	1.667
0.9*c*	2.294
0.95*c*	3.203
0.99*c*	7.089

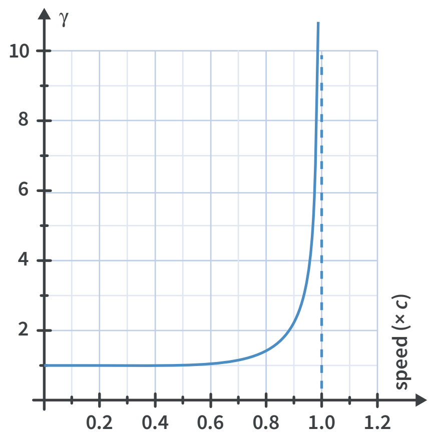


Figure 2 The Lorentz factor increases with speed and approaches infinity as speed approaches *c*.

USEFUL TIP

It can be helpful to have a similar table to Table 1 in your pre-written exam notes so that you can check the appropriateness of your calculations for the Lorentz factor.

Length contraction 3.3.10.1 & 3.3.11.3

OVERVIEW

Due to the effects of special relativity, observers in reference frames which are moving relative to each other will measure different lengths of the same object. Proper length is the length of an object measured by an observer who is at rest relative to the object. An observer in any other reference frame will measure the same object to have a contracted (shorter) length in the direction of motion.

THEORY DETAILS

The **proper length** or **rest length**, L_0, describes the length of an object measured by an observer who is at rest relative to the object. That is, the length measured by an observer who is in the same reference frame as the object being measured.

In any reference frame that is moving relative to the object, an observer will measure the object to be contracted in the direction of motion. It is important to understand that the contracted length is still a correct measurement – in this sense the term 'proper length' can be misleading.

Consider the relative motion of Rachel in a red car and Bob in a blue bus shown in Figure 3. Remember that speed is relative, and that Bob and Rachel (who are both in inertial frames of reference) have equal claim to being at rest while the other vehicle is in motion.

For measurements of the **length of the blue bus**:

- **Bob** measures the **proper length**, L_0, because he and the blue bus are at rest relative to each other.
- Rachel measures a contracted length, L, because she is moving relative to the blue bus (she and the blue bus are in different reference frames).

Now compare this with measurements of the **length of the red car**:

- Bob measures a contracted length, L, because he is moving relative to the red car (he and the red car are in different reference frames).
- **Rachel** measures the **proper length**, L_0, because she and the red car are at rest relative to each other.

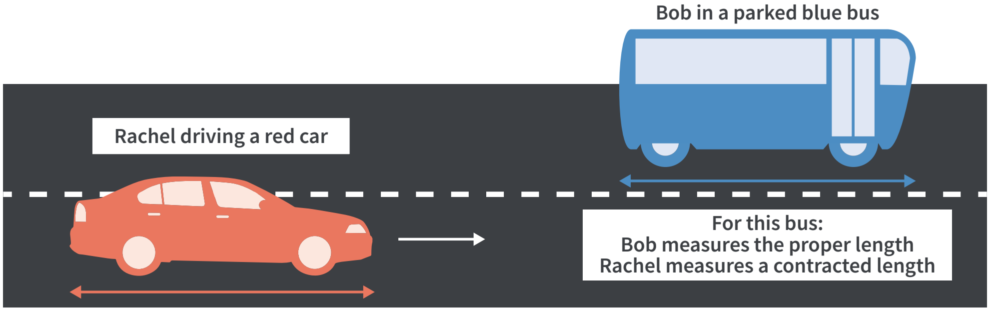


Figure 3 Rachel is driving a red car at a constant velocity and she passes Bob who is sitting in a parked blue bus. This diagram depicts the red car as moving and the bus at rest, but both vehicles are in inertial reference frames. Therefore Bob and Rachel can each claim that he/she is at rest and the other vehicle is in motion.

The relationship between proper length and the contracted length measured by an observer in a different reference frame is given by the following equation.

$$L = \frac{L_0}{\gamma}$$

L = contracted length (m), L_0= proper length (m), γ = Lorentz factor (no units)

There are some important points to emphasise here:

- Length contraction occurs **only** in the direction of motion.
- The contracted length, L, is always **shorter** than the proper length, L_0.
- The proper length is measured if the object is at rest in the given frame of reference, while the contracted length is measured if the object is in motion in the given frame of reference.
- All observers agree on the relative speed, v, between reference frames. They just disagree about which reference frame is moving.

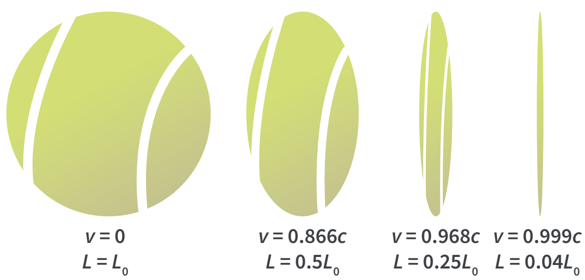
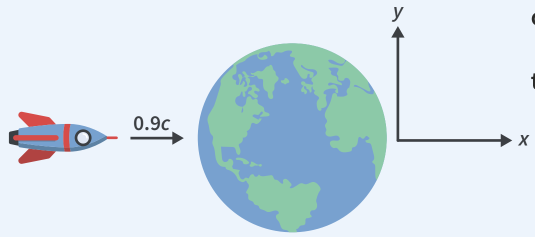


Figure 4 As the relative velocity of the tennis ball increases the measured length of the tennis ball decreases in the direction of motion. Note that the other dimensions of the tennis ball do not change.

1 Worked example

A spaceship is travelling towards Earth at 0.9*c*. An astronaut on board the spaceship and an observer on Earth both measure the length of the spaceship and the diameter of the Earth in the *x*-direction.



Take the Earth's diameter to be 1.3×10^7 m as measured by the observer on Earth.

a **Who measures the proper length of the spaceship?**

b **Who measures the proper length (diameter in the *x*-direction) of the Earth?**

c **What is the diameter of the Earth in the *x*-direction as measured by the astronaut?**

d **What is the diameter of the Earth in the *y*-direction as measured by the astronaut?**

a The astronaut – the spaceship is at rest relative to the astronaut.

b The observer on Earth – the Earth is at rest relative to the observer.

c The astronaut measures a contracted diameter in the *x*-direction because the spaceship is moving relative to the Earth in this direction.

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.9c)^2}{c^2}}} = \frac{1}{\sqrt{1-0.9^2}} = 2.294$$

Note that the Lorentz factor can also be obtained from Table 1.

$$L = \frac{L_0}{\gamma} = \frac{1.3 \times 10^7}{2.294} = 5.7 \times 10^6 \text{ m}$$

d 1.3×10^7 m. The astronaut and the observer agree on the diameter of the Earth in the *y*-direction since the spaceship is not moving in the *y*-direction relative to the Earth.

Time dilation 3.3.9.1 & 3.3.11.2

OVERVIEW

Observers in reference frames which are moving relative to each other will measure different time intervals between the same two events. Proper time refers to the **time interval** between two events measured by an observer for whom the two events occur at the same location in space. An observer in any other reference frame will measure a dilated (greater) time interval between the same two events.

THEORY DETAILS

Proper time is the **time interval between two events,** as measured by an observer for whom the **two events occur at the same location in space**.

An event is something that occurs at a particular location and time.

Examples of events include: a rocket arriving on the surface of a planet, a clock hand "striking 12", a collision between two vehicles, and a lightning strike.

To determine if an observer in an inertial reference frame measures proper time:

1. Identify the two events that occur which define the time interval (start and end) being measured.
2. If the two events occur at the same distance and direction from the observer, then the observer will measure the proper time interval.
3. If the two events occur at a different distance or direction from the observer, then the observer will measure a dilated time interval.

Consider the relative motion of Rachel in a red car and Bob in a blue bus shown in Figure 5. For measurements of the time interval between the front of the car passing the back of the bus and then passing the front of the bus:

- Bob measures a dilated time, t, because event 1 happens behind him and event 2 happens in front of him.
- **Rachel** measures the **proper time**, t_0, because the two events happen at the same position/distance relative to her (both events occur at the front of her car).

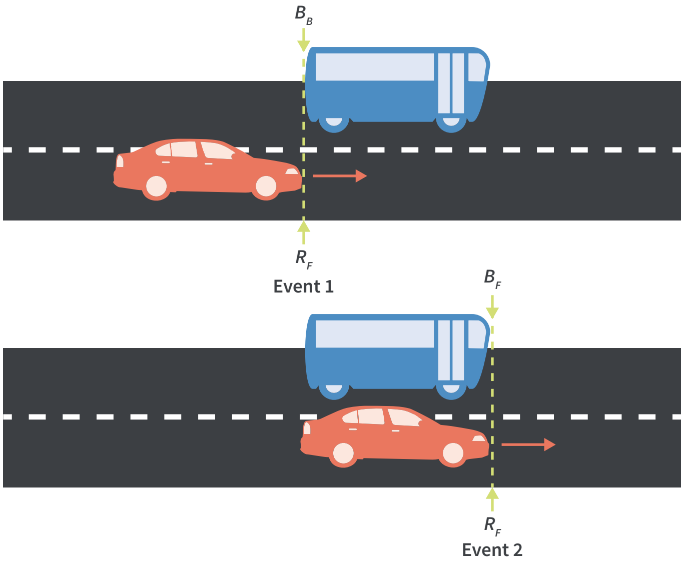


Figure 5 B_F represents the front of Bob's blue bus and B_B represents the back. R_F represents the front of Rachel's red car. Rachel measures the proper time for the front of her car to pass the bus as the two events occur at the same distance from her.

Now compare this with measurements of the time interval between the front of the car passing the back of the bus and then the back of the car passing the back of the bus:

- **Bob** measures the **proper time**, t_0, because the two events happen at the same position relative to him (both events occur at the back of his bus).
- Rachel measures a dilated time, t, because event 1 happens in front of her and event 2 happens behind her.

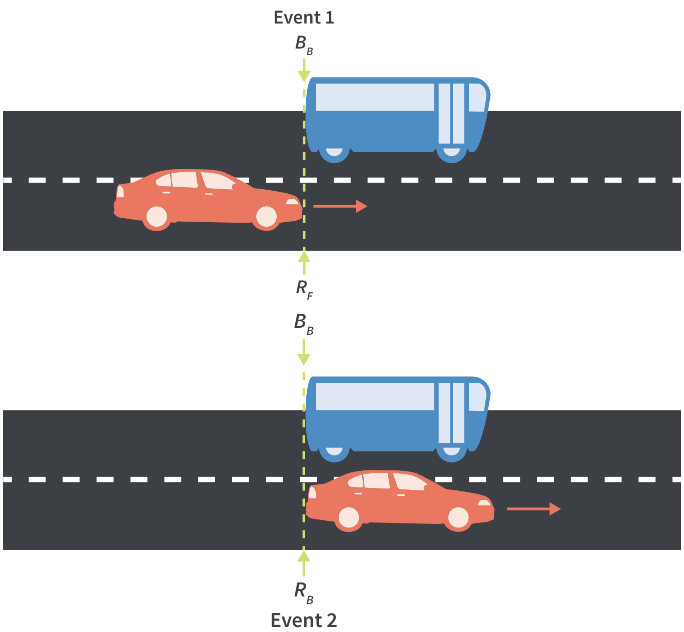


Figure 6 B_B represents the back of Bob's blue bus. R_F represents the front of Rachel's red car and R_B represents the back. Bob measures the proper time for the length of the red car to pass a point on the blue bus as the two events occur at the same distance from him.

The relationship between proper time and the dilated time measured by an observer in a different reference frame is given by the following equation.

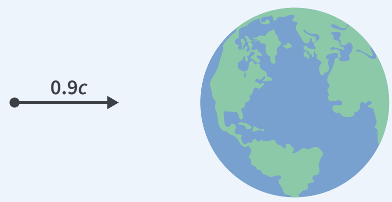
> $t = t_0\gamma$
> **t = dilated time (s), t_0= proper time (s), γ = Lorentz factor (no units)**

There are some important points to emphasise here:

- The dilated time is always **greater** than the proper time.
- Which observer measures proper time depends on the events that are being measured.
- The ordinary formula for calculating speed ($v = \frac{\Delta s}{\Delta t}$) still applies as long as the distance and time measurements are made in the same reference frame.

2 **Worked example**

A particle is created travelling directly towards Earth at 0.9*c*. In Earth's frame of reference the particle decays in 8.1 seconds.



a **Do observers on Earth measure the proper time for the life of the particle? Explain.**

b **Calculate the lifetime of the particle as measured in its own reference frame.**

a Observers on Earth do not measure proper time. The two events are:

1. Creation of the particle

2. Decay of the particle

In the Earth's frame of reference these two events occur at different locations.

b We must use the Lorentz factor to relate the time measured by an observer on Earth to the measurement in the particle's reference frame.

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.9c)^2}{c^2}}} = \frac{1}{\sqrt{1-0.9^2}} = 2.294$$

Proper time is measured in the particle's reference frame. We are given the dilated time of 8.1 s.

$t = t_0\gamma$

$8.1 = t_0 \times 2.294$

$t_0 = 3.5$ s

Muon detection as evidence for special relativity 3.3.12.1

OVERVIEW

Muons provide observable evidence of time dilation and length contraction. Classical physics predicts that most muons would decay before reaching Earth's surface. Scientists, in fact, observe that many more muons reach the surface before decaying than classical physics would predict. These observations can be explained by special relativity.

THEORY DETAILS

A muon is a subatomic particle created in the upper atmosphere by cosmic rays hitting an atmospheric molecule. When they are created they are travelling at close to the speed of light. The half-life of a muon is 2.2×10^{-6} s. Classical physics predicts that most muons should decay before they reach the Earth's surface.

What special relativity predicts

From the Earth's frame of reference, time dilation means the muons are measured to have a longer life. As such, the muons will travel further than predicted by classical physics before decaying and so more muons will reach the surface.

OR

From the muon's frame of reference, length contraction means the distance to the surface is reduced. As such, more muons than predicted by classical physics can travel the distance to the surface before decaying.

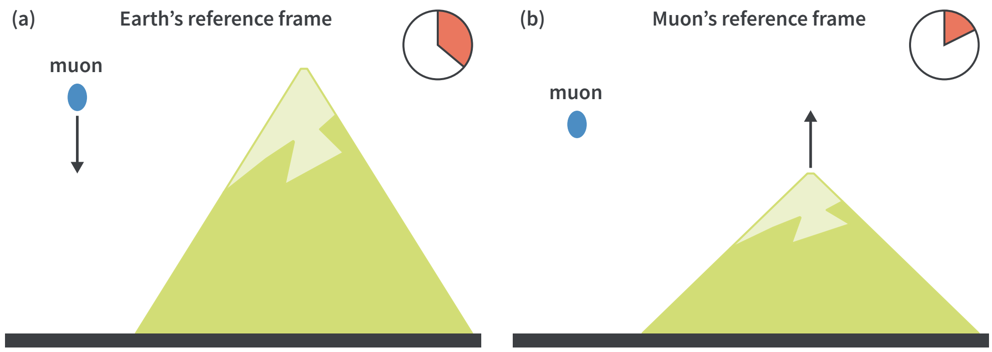


Figure 7 **(a)** From the Earth's reference frame the muon is measured to have a longer life than in the rest frame of the muon. **(b)** From the muon's reference frame the distance to the surface of the Earth is measured to be shorter than in the Earth's frame.

Theory summary

- The Lorentz factor is a dimensionless quantity that determines the amount of time dilation and length contraction.
  - $\gamma = \dfrac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
  - For an object at rest the Lorentz factor is 1.
  - The Lorentz factor approaches infinity as an object approaches the speed of light.
- Proper length is the length that is measured in the frame of reference in which objects are at rest.
- Proper time is the time interval between two events in a. reference frame where the two events occur at the same point in space.
- Contracted length can be calculated by: $L = \dfrac{L_0}{\gamma}$.
- Dilated time can be calculated by: $t = t_0\gamma$.
- Muons provide experimental evidence of special relativity.
  - More muons are detected at the Earth's surface than predicted by classical physics.
  - From the Earth's frame of reference, time dilation increases the lifespan of muons.
  - From the muon's frame of reference, length contraction decreases the distance it must travel to reach Earth's surface.

KEEN TO INVESTIGATE?

YouTube video: PBS Space Time – When Time Breaks Down
https://youtu.be/GguAN1_JouQ

YouTube video: Sixty Symbols – Relativity Paradox
https://youtu.be/kGsbBw1I0Rg

YouTube video: minutephysics – Special Relativity Ch. 3 | Lorentz Transformations
https://youtu.be/Rh0pYtQG5wI

YouTube video: minutephysics – Special Relativity Ch. 4 | Relativity of Simultaneity
https://youtu.be/SrNVsfkGW-0

YouTube video: minutephysics – Special Relativity Ch. 5 | Length Contraction and Time Dilation
https://youtu.be/-NN_m2yKAAk

4B Questions

THEORY REVIEW QUESTIONS

Question 1

What units are used to measure the Lorentz factor (γ)?

A m s^{-1}

B m s

C $\text{N m}^{-1}\text{ s}^{-1}$

D The Lorentz factor is dimensionless

Question 2

As an object with mass approaches *c*, its Lorentz factor approaches

A 0.

B 1.

C 100.

D infinity.

Question 3

The Lorentz factor for an object at rest is

A -1.

B 0.

C 1.

D 2.

Question 4

Proper time is best defined as

A the time interval between two events in a reference frame where the two events occur at the same point in space.

B the time interval between two events in the reference frame of a stationary observer.

C the longest possible time interval between two events that any observer can measure.

D the time between two events within the observer's frame of reference.

Question 5

Proper length is best defined as

A the shortest possible length that an observer measures an object to be.

B the length as measured by an observer in motion.

C the length that is measured in the frame of reference in which objects are at rest.

D proper length of an object is dependent on an observer's frame of reference.

Question 6

In order to find the velocity of an object travelling at $0.3c$ in m s^{-1}, what operation must we perform?

A Multiply by 3.0×10^8

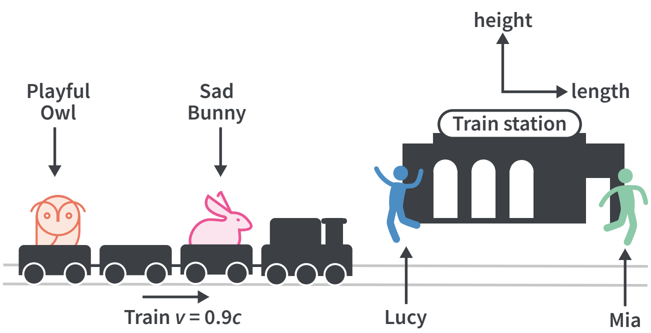
B Divide by 3.0×10^8

C Add 3.0×10^8

D Subtract 3.0×10^8

Use the following information to answer Questions 7–11.

The diagram shows a (very fast) train moving to the right, with Sad Bunny at the front and Playful Owl at the back, moving past a train platform. Lucy is at the left end of the platform and Mia at the right end. In Questions 7–10 you will need to identify one or more characters.



Question 7

Identify the character(s) who measure the proper length of the train.

Question 8

Identify the character(s) who measure the proper length of the train station.

Question 9

Identify the character(s) who measure the proper time between the front of the train passing Lucy and then the back of the train passing Lucy.

Question 10

Identify the character(s) who measure the proper time between the front of the train passing Lucy and then the front of the train passing Mia.

Question 11

In which dimension of the station will length contraction be relevant?

A Height

B Length

C Depth

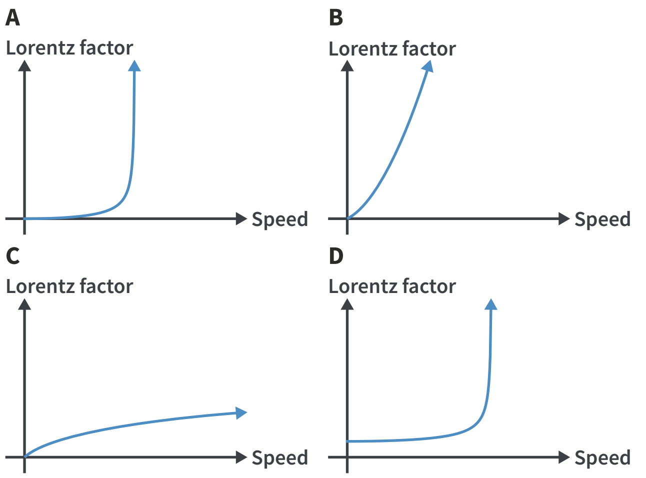
D All of the above

EXAM-STYLE QUESTIONS

This lesson

Question 12 (1 MARK)

Which of the following gives the graph of the Lorentz factor against the speed of a spacecraft as it approaches the speed of light?



Adapted from 2018 VCAA Exam Section A Q13

Question 13 (2 MARKS)

A rocket ship is travelling at 2.786×10^8 m s^{-1}. What is the Lorentz factor of the rocket?

Question 14 (3 MARKS)

A train passes an observer stationary on the side of the track. The observer measures the train's length as one-quarter of the train's rest length. What speed is the train travelling past the observer? Give your answer in metres per second.

Adapted from 2017 VCAA Exam Section B Q10

Question 15 (2 MARKS)

An exoplanet orbits its star five times in 24 hours as measured by scientists on Earth. The star is travelling towards Earth at 0.78*c* (γ = 1.598). Calculate how long it takes the planet to orbit, in the star's frame of reference. Give your answer in hours.

Adapted from 2018 VCAA Exam Section B Q16

Question 16 (2 MARKS)

Two spacecraft are travelling towards each other. Spacecraft 1 has a beacon which flashes once every 5.00 seconds. An observer on spacecraft 2 detects the pulse periodically flashing every 5.72 seconds.

What is the relative speed of the two spacecraft? Give your answer in metres per second.

Question 17 (1 MARK)

A neutrino is travelling towards Earth at 0.5*c* (γ = 1.155). A rocket is travelling towards the same neutrino with a speed of 0.7*c* (γ = 1.400) **relative to the neutrino**. The rocket is 30.00 m long when measured in its own reference frame. What is the rocket's length when measured from the neutrino's reference frame?

A 11.74 m

B 21.43 m

C 25.97 m

D 30.00 m

Question 18 (8 MARKS)

Scientists detect a greater number of muons reaching the Earth's surface than they expect using the classical laws of physics. A muon is created in the atmosphere 10 km above Earth's surface, and is travelling at 0.99*c*. This muon decays in 2.4×10^{-6} s.

a How far does the muon have to travel to reach Earth's surface in the muon's frame of reference? Give your answer in metres. (3 MARKS)

b How long does it take for the muon to decay in the Earth's frame of reference? (2 MARKS)

c Why does special relativity predict that a greater number of muons are able to reach Earth's surface than classical physics predicts? (3 MARKS)

Question 19 (2 MARKS)

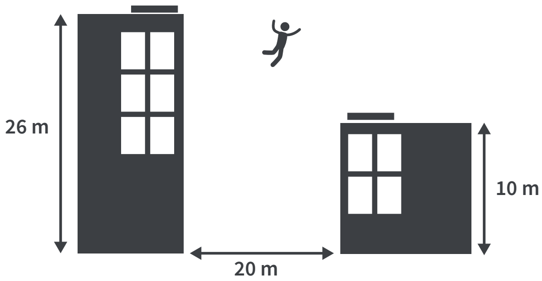
Scientists created a particle travelling at 0.9967*c* and observed it travel a distance of 1.42×10^{-2} m in a straight line before decaying. The particle is not accelerating. Calculate the lifetime of the particle in the scientists' frame of reference.

Adapted from 2017 VCAA Exam Section B Q11a

Previous lessons

Question 20 (4 MARKS)

Jim is jumping between buildings in his role as a stunt performer. He jumps a 20 m gap from a building that is 26 m tall onto a building that is 10 m tall. He jumps with an initial velocity of 17 m s^{-1} horizontally to the right.

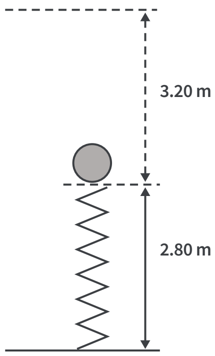


a How long does it take Jim to reach a height of 10 m above the ground? (2 MARKS)

b Will Jim make the jump by landing on the 10 m tall building? Use calculations to support your answer. (2 MARKS)

Question 21 (2 MARKS)

A spring is static with an unknown mass on top. The mass is stationary and has compressed the spring by 3.20 m and the mass is 2.80 m off the ground. The spring constant is 289 N m^{-1}.



Find the value of the unknown mass.

Key science skills

Question 22 (3 MARKS)

Jemma is attempting to experimentally verify the relationship between time dilation and speed. She measures the time to decay at different speeds for a certain particle which has a fixed lifetime of 2.18×10^{-6} seconds when measured in its own reference frame. Her results are shown in a table.

Speed (× *c*)	Time to decay (s)
0	2.18×10^{-6}
0.2	2.28×10^{-6}
0.5	2.54×10^{-6}
0.7	2.98×10^{-6}
0.9	5.07×10^{-6}
0.95	7.03×10^{-6}

Plot Jemma's results. Choose the correct axis for each variable, and include appropriate axis labels and units.

4C MASS-ENERGY

Energy and mass are equivalent and a small amount of matter can be exchanged for a tremendous amount of energy: if one gram was entirely converted to energy, it could provide the energy needed by a city for days. This lesson will explore this mass-energy equivalence and how it is responsible for the radiation emitted by stars like the Sun. It will also introduce the relativistic kinetic energy of an object, which is different from the predictions of classical physics.

4A Special relativity concepts	4B Length contraction and time dilation	4C Mass-energy

Study design key knowledge dot points

- interpret Einstein's prediction by showing that the total 'mass-energy' of an object is given by: $E_{tot} = E_k + E_0 = \gamma mc^2$ where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = \left(\gamma - 1\right)mc^2$
- describe how matter is converted to energy by nuclear fusion in the Sun, which leads to its mass decreasing and the emission of electromagnetic radiation

Key knowledge units

Rest energy	3.3.16.1
Relativistic kinetic energy	3.3.16.2
Total mass-energy	3.3.16.3
Conservation of mass-energy	3.3.17.1
Fusion reactions	3.3.17.2

Formulas for this lesson

Previous lessons		New formulas
3B	* $KE = \frac{1}{2}mv^2$	* $E_0 = mc^2$
4B	* $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$	* $KE = (\gamma - 1)mc^2$
		* $E_{tot} = KE + E_0 = \gamma mc^2$
		$\Delta E = \Delta mc^2$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

fusion see nuclear fusion

mass-energy equivalence the principle that mass can be considered as a form of energy; mass can be converted into energy and energy can be converted into mass

nuclear fusion two nuclei combine to form a different nucleus, releasing energy in the process

rest energy the energy of an object at rest, equivalent to the energy of its mass

total mass-energy the sum of the kinetic and rest energy of a mass

Rest energy 3.3.16.1

OVERVIEW

Any mass m has an equivalent energy equal to $E_0 = mc^2$. This is called the rest energy because it is the energy of any mass that is stationary.

THEORY DETAILS

A consequence of Einstein's theory of special relativity is that mass can be equated to energy using his famous equation $E_0 = mc^2$. Mass is a property of the way that energy behaves under certain conditions. Rest energy is the total energy of a mass excluding kinetic energy.

> $E_0 = mc^2$
>
> **E_0 = rest energy (J), m = mass (kg), c = speed of light (3.0×10^8 m s^{-1})**

The appearance of the c^2 term in this equation tells us that there is a lot of energy even in small amounts of mass. For example, the rest energy of a 1 g mass is 9×10^{13} J. That's more energy than the explosion from 20 kilotons of TNT!

USEFUL TIP

Note that the current VCE study design denotes the rest energy as E_0 or E_{rest}. It does not use the term 'rest mass' or 'relativistic mass', as mass is a constant quantity regardless of speed. These terms may appear in older material, however they should be avoided.

Relativistic kinetic energy 3.3.16.2

OVERVIEW

At relativistic speeds, kinetic energy is found using the formula $KE = (\gamma - 1)mc^2$. From this equation it becomes evident that an object with mass would gain an infinite energy as it approaches the speed of light.

THEORY DETAILS

At low speeds the classical calculation of kinetic energy, $KE = \frac{1}{2}mv^2$, is a good approximation but at extremely high speeds it gives inaccurate results. The formula for relativistic kinetic energy is true for all speeds and it gives significantly different results when speeds are near the speed of light.

> $KE = (\gamma - 1)mc^2$
>
> **KE = kinetic energy (J), γ = Lorentz factor (no units), m = mass (kg), c = speed of light (3.0×10^8 m s^{-1})**

Remembering that the Lorentz factor approaches infinity near the speed of light, we can see from the equation that the kinetic energy also approaches infinity near the speed of light. Since it is impossible to have infinite kinetic energy **no object with mass can move at or faster than the speed of light**. The speed of light is therefore the **speed limit of the universe**.

The graph shows a large disparity in classical and relativistic kinetic energy at relativistic speeds.

Because the classical kinetic energy is accurate at non-relativistic speeds, we can use the classical formula to find kinetic energy in most scenarios. But when dealing with high speed scenarios, we have to use the relativistic kinetic energy formula.

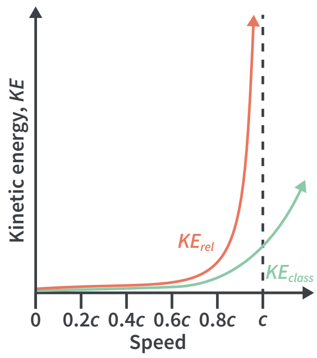


Figure 1 A comparison of classical and relativistic predictions of kinetic energy at speeds ranging from 0 to c.

1 Worked example

An object with mass 2.0 kg is travelling at 2.0×10^8 m s^{-1}. Calculate

a **the kinetic energy of the object as predicted by classical physics.**

b **the actual kinetic energy of the mass according to special relativity.**

a $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 2.0 \times (2.0 \times 10^8)^2 = 4.0 \times 10^{16}$ J

b $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(2.0 \times 10^8)^2}{(3.0 \times 10^8)^2}}} = 1.34$

$KE = (\gamma - 1)mc^2 = (1.34 - 1) \times 2.0 \times (3.0 \times 10^8)^2 = 6.1 \times 10^{16}$ J

Total mass-energy 3.3.16.3

OVERVIEW

If an object with mass is moving, its total energy is the sum of its rest energy and its kinetic energy.

THEORY DETAILS

The total mass-energy of an object that has mass is the sum of its rest energy and its kinetic energy. We know that $E_0 = mc^2$ and $KE = (\gamma - 1)mc^2$, so adding these together the total mass-energy is equal to:

$$E_{tot} = \gamma mc^2$$

E_{tot} = total mass-energy (J), γ = Lorentz factor (no units), m = mass (kg), c = speed of light (3.0×10^8 m s^{-1})

2 **Worked example**

An object with mass 3.0 kg is travelling at 2.5×10^8 m s^{-1}. Calculate the total mass-energy of the object.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(2.5 \times 10^8)^2}{(3.0 \times 10^8)^2}}} = 1.81$$

$$E_{tot} = \gamma mc^2 = 1.81 \times 3.0 \times (3.0 \times 10^8)^2 = 4.9 \times 10^{17} \text{ J}$$

Conservation of mass-energy 3.3.17.1

OVERVIEW

Mass can be converted into other forms of energy. Although we have learned that mass and energy are always conserved, it is really mass-energy that is always conserved.

THEORY DETAILS

When studying classical physics, we assumed that for a given system, the total mass of the system is conserved. However, with the introduction of special relativity we know that mass is just a property that energy exhibits and so the assumption of mass conservation is not always correct. Rather the total **mass-energy** of a system is conserved. This means that the mass of a system can be converted into other forms of energy, and vice versa.

If the mass in a system changes, we can calculate the change in other forms of energy by manipulating the rest energy 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})

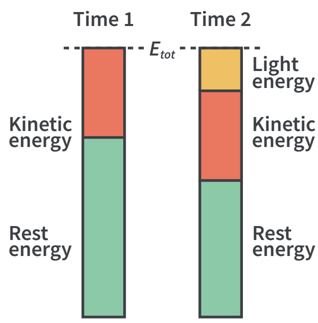


Figure 2 The total mass-energy of a system is conserved. Some rest energy (from a mass) is converted into light energy, but the total mass-energy is conserved.

Fusion reactions 3.3.17.2

OVERVIEW

In the Sun, and other stars, mass is continuously converted into energy by fusion reactions.

THEORY DETAILS

A fusion reaction is the combination of two nuclei to form a different nucleus. Inside the Sun, lighter elements undergo fusion to create heavier elements releasing energy in the process. The sum of the mass of the particles that combine in a fusion reaction is greater than the sum of masses after the reaction. We can use the formula $\Delta E = \Delta mc^2$ to calculate the energy released in a fusion reaction.

Because fusion reactions constantly occur in the Sun, its mass decreases over time. The Sun loses approximately 1.89×10^{17} kg of mass per year, which corresponds to a release of approximately 1.70×10^{34} J of energy in the form of light (electromagnetic radiation) per year.

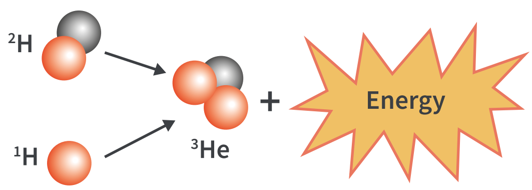


Figure 3 A simplified fusion reaction that occurs inside the Sun. Two hydrogen atoms undergo fusion to create helium, releasing energy.

Theory summary

- Mass is a property that energy exhibits.
- Rest energy is calculated by $E_0 = mc^2$.
- Relativistic kinetic energy is given by $KE = (\gamma - 1)mc^2$ and increases to approach infinity as the speed approaches the speed of light (c).
- Relativistic and classical kinetic energy produce almost identical results at low speeds, but at relativistic speeds classical kinetic energy becomes inaccurate.
- Total mass-energy is always conserved and can be calculated by $E_{tot} = KE + E_0 = \gamma mc^2$.
- Mass can be converted into energy and vice versa, with $\Delta E = \Delta mc^2$.
- Fusion reactions occur within the Sun, converting mass into other forms of energy.

KEEN TO INVESTIGATE?

YouTube video: Elearnin – Nuclear fusion
https://youtu.be/Cb8NX3HiS4U

YouTube video: PBS Space Time – The Real Meaning of $E = mc^2$
https://youtu.be/Xo232kyTsO0

YouTube video: PBS Space Time – The True Nature of Matter and Mass
https://youtu.be/gSKzgpt4HBU

4C Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following statements is **incorrect**?

A Total mass-energy is the sum of kinetic and rest energy.

B Mass is conserved in a closed system.

C Total mass-energy is conserved in a closed system.

D Relativistic kinetic energy can be calculated at all speeds below c.

Question 2

The relativistic kinetic energy of a neutron with a velocity close to c is

A less than its classical kinetic energy.

B greater than its classical kinetic energy.

C equal to its classical kinetic energy.

D not able to be determined.

Question 3

The Sun loses mass over time due to the

A fission reactions inside its core.

B fusion reactions inside its core.

C allergic reactions inside its core.

D radioactive decay inside its core.

Question 4

Which of the following statements is **correct**?

A Rest energy is the equivalent energy of a mass at rest.

B Rest energy is the equivalent energy of a mass moving in an inertial reference frame.

C Rest energy increases as speed increases.

D Rest energy decreases as speed increases.

EXAM-STYLE QUESTIONS

This lesson

Question 5 (2 MARKS)

Can a particle with mass be accelerated to the speed of light? Explain why or why not.

Question 6 (1 MARK)

The relationship between a particle's mass and its total energy is given by:

$$E_{tot} = \gamma mc^2, \text{ where } \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

It takes 0.2 J to increase the speed of a molecule from 0.80c to 0.81c, but it takes 11 J to increase its speed from 0.98c to 0.99c even though the change in speed is the same. What is the best explanation for why this disparity occurs?

A The total energy of the molecule increases with γ, which increases rapidly as speeds approach c.

B Kinetic energy is equal to mv^2, so at higher speeds it requires more energy to increase the velocity.

C The particle's kinetic energy is directly proportional to its velocity.

D The particle gains mass as it speeds up according to special relativity.

Adapted from 2011 VCAA Exam 1 Section B Detailed study 1 Q2

Question 7 (2 MARKS)

Calculate the total energy of a proton with mass 1.67×10^{-27} kg travelling at 0.80*c*.

Question 8 (2 MARKS)

The star Alpha Centauri A emits an average of 4.20×10^{26} J of electromagnetic radiation every second. What is the corresponding rate at which mass inside this star is lost? Write your answer in kg s^{-1}.

Question 9 (1 MARK)

An atom has an initial mass *m* before emitting 2.7×10^{-12} J of energy. What is the new mass of the atom?

A $m - 9.0 \times 10^{-21}$ kg

B $m + 3.0 \times 10^{-29}$ kg

C $m - 3.0 \times 10^{-29}$ kg

D $m - 2.4 \times 10^{5}$ kg

Adapted from 2015 VCAA Exam Section B Detailed study 1 Q9

Question 10 (3 MARKS)

An ion with mass 2.34×10^{-27} kg is accelerated so that its Lorentz factor is increased from $\gamma = 1.40$ to $\gamma = 2.30$. Calculate the work done to accelerate the ion.

Question 11 (3 MARKS)

A neutron has a mass of 1.67×10^{-27} kg and relativistic kinetic energy of 1.8×10^{-10} J. What is the speed of the neutron?

Question 12 (4 MARKS)

Calculate the difference between the classical and relativistic kinetic energy of an atom with mass 3.34×10^{-27} kg travelling at 0.8*c*.

Question 13 (2 MARKS)

A particle has kinetic energy that is 12 times its rest energy. Calculate the Lorentz factor of this particle.

Adapted from 2019 VCAA NHT Exam Section A Q18

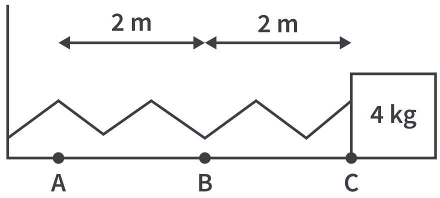
Previous lessons

Question 14 (2 MARKS)

Calculate the magnitude of the momentum of an asteroid with mass 3.0×10^{8} kg travelling at 2.8×10^{4} km h^{-1} towards the town of Benalla.

Question 15 (4 MARKS)

Calculate the kinetic and strain potential energy when an oscillating mass of 4 kg, attached to a spring, is at points A, B and C. At point C, the speed of the mass is 0 m s^{-1}. At point B, the spring is in its unstretched position. Ignore friction. Assume $k = 100$ N m^{-1} in both compression and extension.

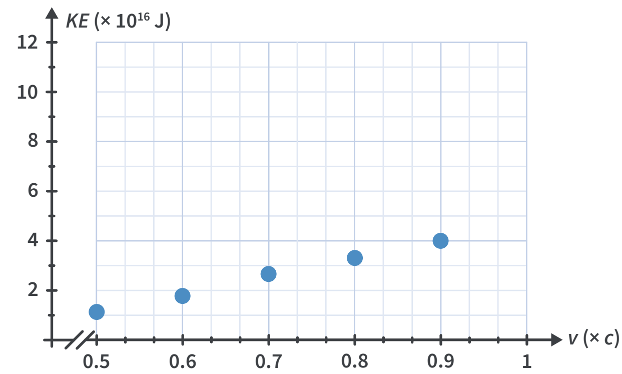


Point	*KE* (J)	*SPE* (J)
A		
B		
C		

Key science skills

Question 16 (3 MARKS)

A graph has been produced showing the classical kinetic energy of an object with a mass of 1 kg at different speeds.



Peta, arguing that using relativistic kinetic energy would produce different results, produces a table with the relativistic kinetic energy at each point on the graph.

Speed (× *c*)	Relativistic *KE* (× 10^{16} J)
0.5	1.39
0.6	2.25
0.7	3.60
0.8	6.00
0.9	11.65

a Plot Peta's energy calculations on a copy of the graph of classical kinetic energy, and include a curve of best fit. (2 MARKS)

b From this graph, what can be determined about how the difference between classical kinetic energy and relativistic kinetic energy compares at different speeds? (1 MARK)

CHAPTER 4 QUESTIONS

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

Consider the motion of three spacecraft.

Spacecraft 1 is accelerating with an initial velocity of 500 km s^{-1}. Spacecraft 2 has a constant velocity of 500 km s^{-1}. Spacecraft 3 has a constant velocity of 900 km s^{-1}.

There is a scientist in each rocket performing the same experiment which involves the motion of a ball. Which of the following statements is known to be true?

A None of the experimental results will agree.

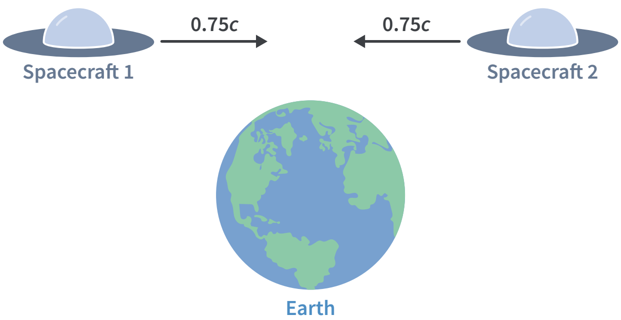
B All of the experimental results will agree.

C Spacecraft 1 and spacecraft 2 experimental results will agree.

D Spacecraft 2 and spacecraft 3 experimental results will agree.

Use the following information to answer Questions 2 and 3.

A scientist from Earth measures that two spacecraft are heading at a constant velocity of 0.75*c* towards each other.



Question 2

The proper time it takes for Spacecraft 1 to pass the Earth's diameter will be measured in the reference frame of

A the scientist on Earth. **B** spacecraft 1.

C spacecraft 2. **D** an absolute universal time.

Question 3

Spacecraft 2 turns on a laser beam. At what speed would a scientist on spacecraft 1 measure the light from the laser to be travelling?

A c **B** $1.5c$ **C** $1.75c$ **D** $2c$

Question 4

The lifetime of a stationary pion as measured in the lab is 84 attoseconds. The lifetime of a relativistic pion travelling towards Earth is measured to be 932 attoseconds.

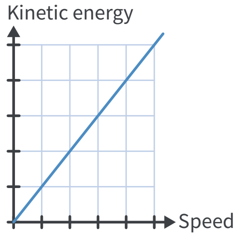
The time dilation observed by scientists gives a Lorentz factor, γ, which is closest to

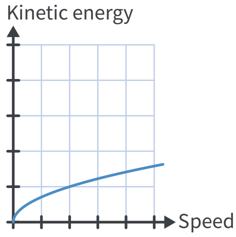
A 1 **B** 11 **C** 111 **D** 1111

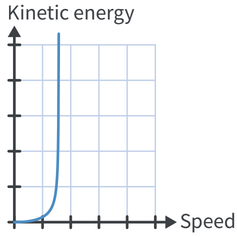
Adapted from 2019 VCAA NHT Exam Section A Q17

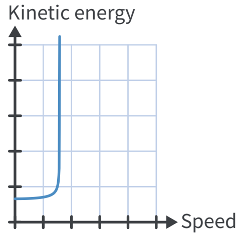
Question 5

Which of the following graphs best represents the kinetic energy versus speed graph as an object approaches the speed of light?

A


B


C


D


Adapted from 2018 VCAA Exam Section A Q13

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 Millennium Falcon spaceship is travelling between star systems 5.84×10^{16} m apart at 0.85*c* in Earth's frame of reference.

a Calculate the time it takes the Millennium Falcon to travel between the star systems as measured by an observer on Earth. (2 MARKS)

b Calculate the time interval that would be observed by Han Solo on board the Millennium Falcon. (3 MARKS)

c Calculate the distance between the star systems that would be measured from the Millennium Falcon's frame of reference. (2 MARKS)

Question 7 (3 MARKS)

Shaniqua is in an inertial frame of reference and observes a rocket moving at a constant velocity. She notes that the clocks on the rocket, which are operating normally, run five times slower than her clocks, which are also operating normally. The rocket has a mass of 8000 kg.

Calculate the kinetic energy of the spaceship in Shaniqua's frame of reference. Show your working.

Adapted from 2018 VCAA Exam Section B Q15

Question 8 (6 MARKS)

A spacecraft is carrying the first humans into interplanetary space from the Earth to the nearest star system, Proxima Centauri, which is 4.24 light-years away from Earth. A light-year is the distance light travels in one year. The astronauts set the spacecraft at a speed which will reach Proxima Centauri in 20.0 years as measured by Earth. Give your answers to three significant figures.

a Show that the spacecraft is travelling at a speed of 0.212*c*. (1 MARK)

b Calculate the duration of the trip for the crew on the spacecraft. Give your answer in years. (3 MARKS)

c What is the distance from Earth to Proxima Centauri as measured by the crew in the spacecraft? Give your answer in light-years. (2 MARKS)

Question 9 (3 MARKS)

Protons in the Large Hadron Collider are accelerated to speeds of over 0.999*c* around a circular track with a circumference of 27 km.

Explain whether these protons are in an inertial frame of reference when they are

- speeding up around the circular track.
- travelling at a constant speed around the circular track.

Question 10 (3 MARKS)

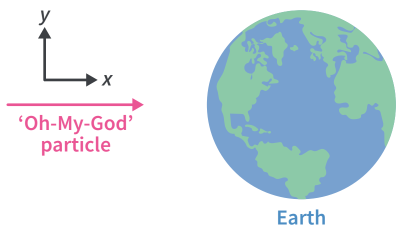
Muons are created in the upper atmosphere travelling at relativistic speeds and can be detected at the surface. They have a half life of 2.2×10^{-6} s. Classical kinematic equations calculate that most muons would not reach the Earth's surface before decaying.

Explain why a greater number of muons are detected at the Earth's surface than classical physics calculates.

Adapted from 2017 VCAA Exam Section B Q11

Question 11 (6 MARKS)

The highest-energy particle ever observed was the 'Oh-My-God' particle. Assume it had a Lorentz factor of $\gamma = 3.2 \times 10^{11}$ and the Earth has a diameter of 12 742 km.



a Determine the diameter of Earth in the ***y*-direction** as measured by the particle's reference frame. (1 MARK)

b Determine the diameter of Earth in the ***x*-direction** as measured by the particle's reference frame. (2 MARKS)

c Calculate the relativistic kinetic energy of the 'Oh-My-God' particle in the Earth's frame of reference if its mass is the same as a proton (1.67×10^{-27} kg). (2 MARKS)

d Determine the 'Oh-My-God' particle's kinetic energy in its own frame of reference. (1 MARK)

Question 12 (6 MARKS)

A rocket accelerates to a maximum speed $0.8c$ with a mass of 530×10^3 kg.

a Calculate the total energy of the rocket when at its maximum speed. (3 MARKS)

b Calculate the equivalent amount of mass which, when converted to energy, could propel the rocket to that speed. (3 MARKS)

Question 13 (3 MARKS)

Describe the process by which energy is created in the Sun.

Question 14 (2 MARKS)

In a nuclear fusion reaction in a star's core, a helium-4 nucleus with a mass of 6.647×10^{-27} kg fuses with a carbon-12 nucleus with a mass of 1.9926×10^{-26} kg to create an oxygen-16 nucleus that has a mass of 2.6563×10^{-26} kg. Ignore the kinetic energy of the nuclei before the reaction. Calculate the energy released. Show your working.

Adapted from 2019 VCAA NHT Exam Section B Q19

Question 15 (3 MARKS)

Before the theory of special relativity was understood it was believed that an object could reach any speed given enough energy. With reference to the Lorentz factor, explain why there is a speed limit for any particle with mass moving through space.

Question 16 (3 MARKS)

In the Sun two deuterium atoms fuse to form tritium and a proton. 6.45×10^{-13} J of electromagnetic radiation is released in the process.

If the tritium atom has a mass of 5.01×10^{-27} kg and the proton has a mass of 1.67×10^{-27} kg, determine the mass of a deuterium atom.

UNIT 3, AOS 3 QUESTIONS

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

What is the magnitude of the displacement of a train with an initial velocity of 12 m s^{-1} that accelerates at a rate of 2 m s^{-2} after 6 seconds?

A 24 m

B 108 m

C 144 m

D 168 m

Adapted from 2016 VCAA Exam Section A Q1

Question 2

A student sits inside a windowless spaceship on a journey to Mars. He conducts a series of motion experiments to investigate frames of reference.

Which one of the following observations is correct?

A The results when the spaceship accelerates are identical to when the spaceship is in uniform motion in a straight line.

B The results when the spaceship accelerates are identical to when the spaceship is at rest.

C The results when the spaceship is at rest differ from when the spaceship is in uniform motion in a straight line.

D The results when the spaceship accelerates differ from when the spaceship is in uniform motion in a straight line.

Adapted from 2017 VCAA Exam Section A Q10

Question 3

Which of these objects is not accelerating?

A A train travelling straight at a constant speed of 50 m s^{-1}

B A car driving around a corner at a constant speed of 20 m s^{-1}

C A plane speeding up as it travels down a runway

D An apple falling from a tree, only under the influence of gravity

Question 4

In which of the following is the best description of when energy is conserved?

A A ball in motion hits another ball of equal mass. The first ball stops and the second ball continues with a speed equal to half of the first ball's original speed.

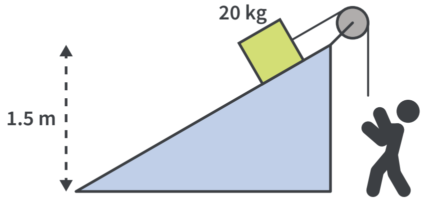
B Two cars have a head-on collision and the front of both of the cars are crushed as they come to a stop.

C Energy is conserved in all situations.

D There is no situation in which energy is conserved.

Question 5

Whilst holding a 20 kg block at the top of a 1.5 m high ramp, a worker is distracted by a loud noise and releases the rope. Which option is closest to the speed of the block at the bottom of the ramp? Ignore any frictional forces.



A $2.5\ \text{m s}^{-1}$

B $5.4\ \text{m s}^{-1}$

C $8.6\ \text{m s}^{-1}$

D $10\ \text{m s}^{-1}$

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 (2 MARKS)

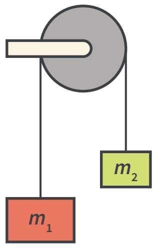
Block *A* has a mass of 30 kg and rests on top of block *B*, which has a mass of 100 kg.

Calculate the magnitude and direction of the force on block *A* by block *B*.

Adapted from 2018 VCAA Exam Section B Q8

Question 7 (6 MARKS)

Darren and Joey utilise a classic experimental setup, an "Atwood machine", to examine the concept of acceleration. They attach two masses, m_1 (500 g) and m_2 (300 g), to a string with negligible mass and hang the masses over a frictionless pulley.



a Calculate the magnitude of the gravitational force on m_1 and m_2 individually. (2 MARKS)

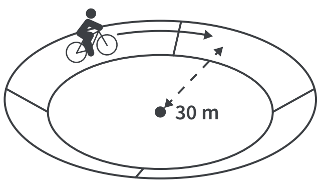
b Calculate the magnitude of the acceleration of m_1. (2 MARKS)

c Calculate the magnitude of the tension in the string. (2 MARKS)

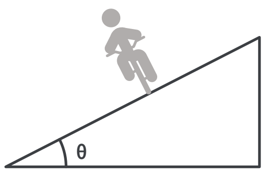
Adapted from 2015 VCAA Exam Section A Q2

Question 8 (6 MARKS)

A bicycle and its rider have a total mass of 120 kg and travel around a circular banked track of 30 m radius. The track is banked at an angle 37.4°.



a On a copy of the diagram, draw all the forces acting on the rider and bicycle. Draw the net force as a dashed line. Considered the bicycle and rider as a single object. (2 MARKS)



b Calculate the speed that the bicycle must travel so that there is no sideways frictional force. (2 MARKS)

c Calculate the magnitude of the net force acting on the bicycle and rider. (2 MARKS)

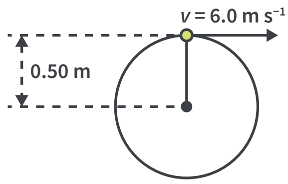
Adapted from 2015 VCAA Exam Section A Q4

Question 9 (6 MARKS)

Students perform an experiment where a ball of mass 1.5 kg is moving in a vertical circle at the end of a string.

The string has a length of 0.5 m.

At the top of the arc, the ball is moving at $6.0\ \text{m s}^{-1}$.



a Does the ball have a great enough speed at the top of the arc so that the string remains tight (under tension)? Support your answer with calculations. (3 MARKS)

b Calculate the speed of the ball at the lowest point. (3 MARKS)

Adapted from 2018 VCAA NHT Exam Section B Q8

Question 10 (3 MARKS)

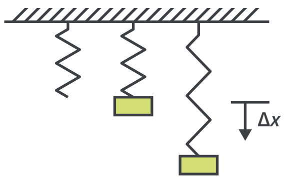
A cannonball (mass 2.0 tonnes) is moving directly upwards at $720\ \text{m s}^{-1}$ when it is at an altitude of 530 m above the ground. After reaching its maximum altitude, the cannonball falls straight back down.

Find the maximum kinetic energy of the cannonball before it hits the ground. Ignore the effects of air resistance in your calculations.

Question 11 (4 MARKS)

Jeremy and Talia hang a mass on the end of a spring. They hold the mass at the unstretched length of the spring and release it, allowing it to fall.

Explain how the three energies involved and the **total energy of the mass** varies as the mass falls from top to bottom. Calculations are **not** required.



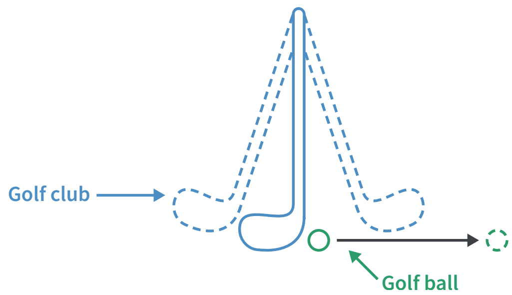
Adapted from 2017 VCAA Exam Section B Q13

Question 12 (5 MARKS)

Students are studying the behaviour between a golf club hitting a stationary golf ball. Treat it as a collision between the head of the golf club and golf ball only. The golf ball is stationary before the collision.

The students take the following measurements

Mass of head of golf club	330 g
Mass of golf ball	45 g
Initial velocity of golf club	$70\ \text{m s}^{-1}$ to the right
Final velocity of golf club after hitting golf ball	$60\ \text{m s}^{-1}$ to the right



a Show that after the collision, the ball's speed is $73\ \text{m s}^{-1}$. (2 MARKS)

b Take $73\ \text{m s}^{-1}$ as the speed of the golf ball after the collision. Use calculations to determine whether or not the collision was elastic. (3 MARKS)

Adapted from 2018 VCAA NHT Exam Section B Q7

Question 13 (2 MARKS)

An alien spaceship travels towards Earth at 80% the speed of light. At a distance of 6.0×10^9 m away from Earth (from Earth's frame of reference), the aliens send a signal in the form of a laser beam.

How long does it take for the laser beam to reach Earth according to a person on Earth?

Adapted from 2018 VCAA NHT Exam Section A Q11

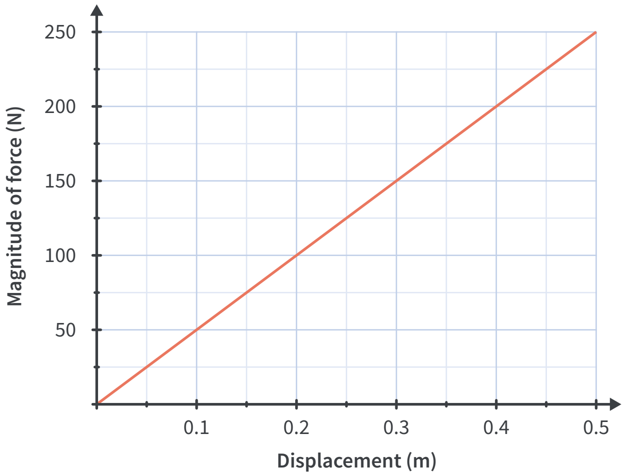
Question 14 (2 MARKS)

The length of a rocket is measured to be one-fifth of its rest length as it passes a planet. What is the speed of the rocket, as determined by an observer on the planet?

Adapted from 2017 VCAA Exam Section B Q10

Question 15 (6 MARKS)

A soccer ball is launched from a vertical spring. The spring characteristics are plotted in the included graph. The spring is initially compressed down by 0.40 m below its natural length. Take the mass of the soccer ball to be 0.40 kg.



a Use the graph to determine the spring constant, k. (2 MARKS)

b What is the elastic potential energy before the soccer ball is launched? (2 MARKS)

c What is the maximum height that the soccer ball reaches above the launcher? (2 MARKS)

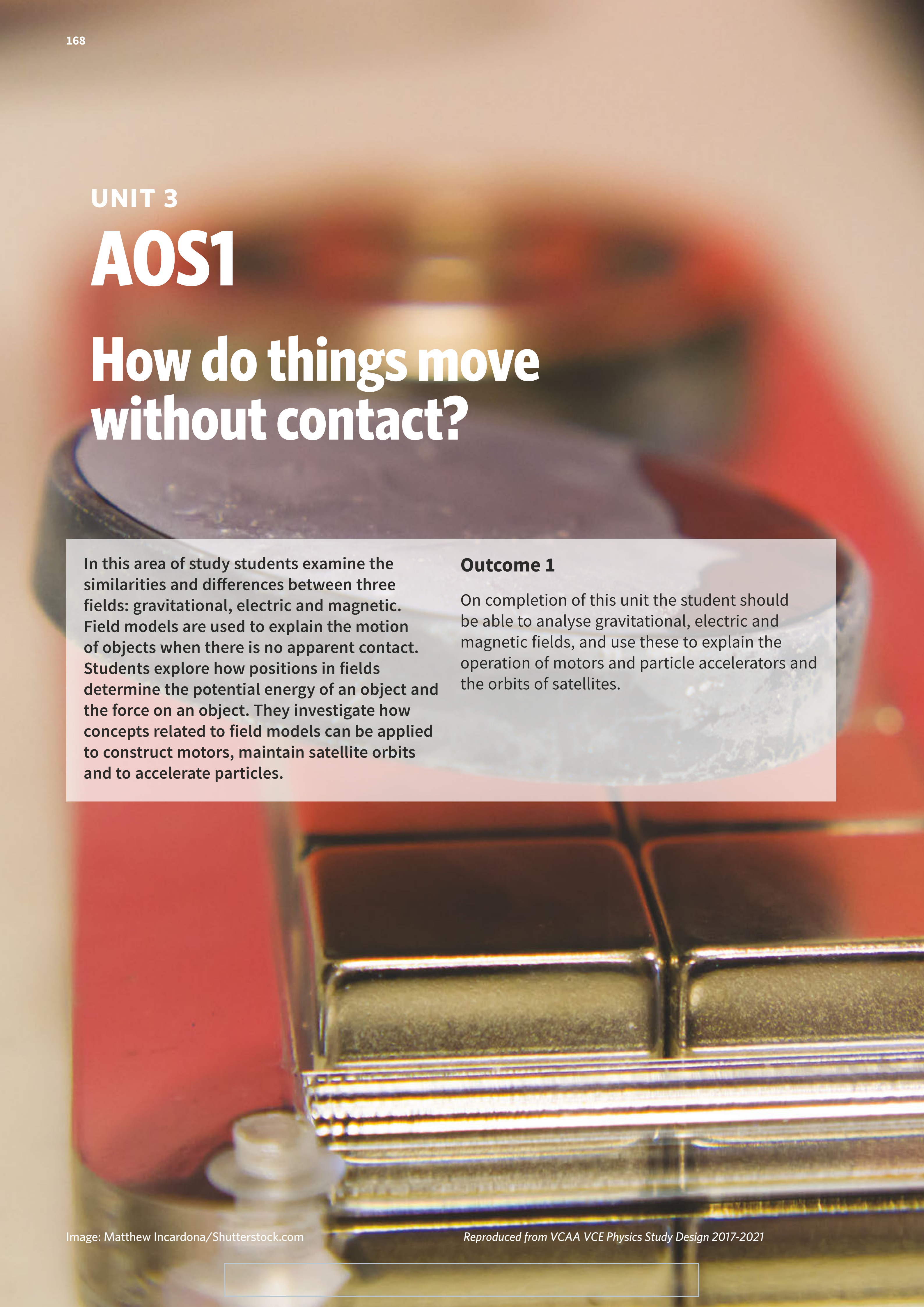
Adapted from 2016 VCAA Exam Section A Q4

Question 16 (3 MARKS)

A scientist in an inertial frame of reference observes a train moving past her at a constant velocity.
She observes that the train is moving at a constant velocity of 2.68×10^5 km s^{-1}. The train has a mass of 4.9×10^5 kg.

Calculate the kinetic energy of the train in the scientist's frame of reference.

Adapted from 2018 VCAA Exam Section B Q15



UNIT 3

AOS1

How do things move without contact?

In this area of study students examine the similarities and differences between three fields: gravitational, electric and magnetic. Field models are used to explain the motion of objects when there is no apparent contact. Students explore how positions in fields determine the potential energy of an object and the force on an object. They investigate how concepts related to field models can be applied to construct motors, maintain satellite orbits and to accelerate particles.

Outcome 1

On completion of this unit the student should be able to analyse gravitational, electric and magnetic fields, and use these to explain the operation of motors and particle accelerators and the orbits of satellites.

Image: Matthew Incardona/Shutterstock.com

UNIT 3 AOS 1, CHAPTER 5

Gravitational fields

05

Key knowledge

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
  - the change in gravitational potential energy from area under a force-distance graph and area under a field-distance graph multiplied by mass
- apply the concepts of force due to gravity, F_g, and normal reaction force, F_N, including satellites in orbit where the orbits are assumed to be uniform and circular
- model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$

Image: Dima Zel/Shutterstock.com

5A GRAVITATIONAL FIELDS AND FORCES

This lesson introduces us to Newton's law of universal gravitation. Every object with mass produces its own gravitational field, attracting all other objects to itself. We will learn how to represent a gravitational field with a field diagram, calculate the gravitational field strength at each point in space, and calculate the gravitational force acting on a body.

5A Gravitational fields and forces	5B GPE in non-uniform fields	5C Orbital motion

Study design key knowledge dot points

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
  - the change in gravitational potential energy from area under a force-distance graph and area under a field-distance graph multiplied by mass
- apply the concepts of force due to gravity, F_g, and normal reaction force, F_N, including satellites in orbit where the orbits are assumed to be uniform and circular

Key knowledge units

The field model of gravity	3.1.1.1 & 3.1.2.1 & 3.1.5.1
Gravitational force and field strength	3.1.8.1
The inverse square law	3.1.3.1
The normal force in gravitational fields	3.1.9.2

Formulas for this lesson

Previous lessons		New formulas
2B	$F_g = mg$	* $g = G\frac{M}{r^2}$
		* $F = G\frac{M_1 M_2}{r^2}$
		$g_2 = \frac{g_1}{n^2}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

dipole a source (field lines point away) and a sink (field lines point towards) paired together

field a region of space in which each point is subject to a non-contact force

gravitational field strength a measure of the gravitational force that acts on each unit of mass at a point in space

monopole a source (field lines point away) or a sink (field lines point towards) of a field in isolation

Newton's law of universal gravitation law that states that every object with mass attracts every other object with mass by a gravitational force that increases with the product of their masses and decreases with the square of the distance between the objects

non-uniform field a field for which the direction and/or magnitude is different at different locations in space

uniform field a field for which both the direction and magnitude are constant throughout the region of space

The field model of gravity 3.1.1.1 & 3.1.2.1.1 & 3.1.5.1

OVERVIEW

A field is a way of modelling a region of space in which each point is subject to a non-contact force. All objects with mass create a gravitational field that attracts all other objects with mass. We can model the gravitational fields of objects with field diagrams.

THEORY DETAILS

Field model conventions

In VCE Physics we need to consider three types of non-contact forces: gravitational force, electric force, and magnetic force. These non-contact forces can all be **modelled** as fields which consist of field lines with the following characteristics.

- Field lines are **vectors** with both direction and magnitude (field strength).
- Field lines are drawn with arrows to indicate the direction of the field.
- Field lines that are **closer together** indicate a **stronger field**.
- Field lines that are **further apart** indicate a **weaker field**.
- Field lines **never intersect or touch** – if they did then it would indicate a point where the field (and therefore the force) points in two different directions.

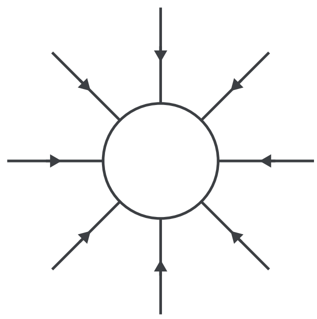


Figure 1 The gravitational field lines point towards the centre of a mass, and are equally spaced around the sphere.

A **monopole** is an object which is **either** the source of a field (meaning the field lines point away from it) **or** the sink of a field (meaning the field lines point towards it), but not both. A **dipole** describes a source and a sink which are paired together.

Drawing gravitational fields

Mass is a gravitational monopole since gravity is always an attractive force. When drawing a gravitational field, these rules should be followed.

- Gravitational field lines must be equally spaced around the surface of spherical objects
- Gravitational field lines point in the direction that another mass would experience a gravitational force at that point in space
- For a single body, all field lines are straight and point directly towards the centre of the mass which means the field lines are typically perpendicular to the surface of a sphere
- Gravitational fields extend infinitely far out into space, so the gravitational field lines should be drawn with an appropriate length to represent that
- Gravitational field lines are usually drawn so that they end on the surface of the object

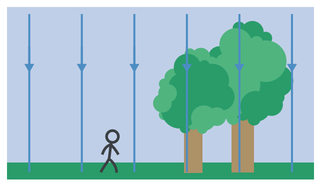


Figure 2 The gravitational field lines appear equidistant and parallel to each other, indicating an approximately uniform gravitational field near the surface of the Earth.

Uniform and non-uniform fields

A uniform field is a field which has a constant strength and direction at all points. When representing a uniform field, all lines are evenly spaced and parallel to each other.

Gravitational fields are **approximately uniform within small regions** near the surface of a planet. This is shown shown in Figure 2.

In a non-uniform field the strength and direction of the field depends on the location. To represent a non-uniform field, the field lines point in different directions and are closer in some regions than others.

While gravitational fields are approximately uniform in small regions, in reality they are not uniform. Figure 3 shows the gravitational field lines around the Earth which point radially towards the centre and are closer to each other near the surface than far away.

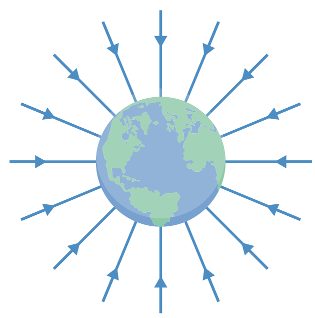


Figure 3 Gravitational field lines showing the field strength around the Earth. As the distance from Earth increases the field lines become further apart, indicating a decrease in the strength of the gravitational field.

Gravitational force and field strength 3.1.8.1

OVERVIEW

The gravitational field strength of a body describes the gravitational force per unit of mass that would act on another object at a point in the field. It can be calculated for any point in space if the mass of the body is known. From this the force due to gravity that acts on a body can be calculated.

THEORY DETAILS

Gravitational field strength

Gravitational field strength, g, describes the magnitude of the gravitational field – that is, the magnitude of the force that acts on each kilogram at a particular location in a gravitational field.

$$g = G\frac{M}{r^2}$$

g = gravitational field strength (N kg^{-1} or m s^{-2}), G = gravitational constant (6.67 × 10^{-11} N m^2 kg^{-2}), M = mass of object creating gravitational field (kg), r = distance from centre of object (m)

Note that gravitational field strength depends on only one mass (the mass creating the field) and is independent of the mass of the object which is in, or 'experiencing', the field. For the purpose of VCE Physics, the gravitational field will always originate from the centre of a mass.

Force due to gravity

We can calculate the gravitational force acting on an object by multiplying the mass of the object by the gravitational field strength at that point ($F_g = mg$).

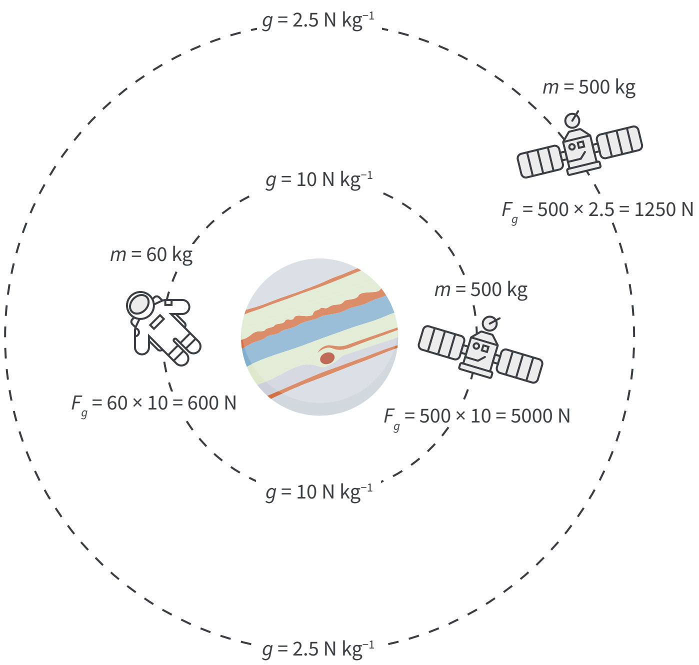


Figure 4 The gravitational field strength (g) has a constant value on the concentric circles. The force due to gravity is calculated by multiplying the mass and the field strength.

Combining the formula for gravitational field strength ($g = G\frac{M}{r^2}$) with the formula for the gravitational force acting on a mass ($F_g = mg$) we can establish **Newton's law of universal gravitation**:

$$F = G\frac{M_1 M_2}{r^2}$$

F = force due to gravity (N), G = gravitational constant (6.67 × 10^{-11} N m^2 kg^{-2}), M_1 = mass of one object (kg), M_2 = mass of other object (kg), r = distance between centres of objects (m)

Note that which object is designated as M_1 and which is M_2 does not matter because the two objects exert the same magnitude of gravitational force on each other. This is consistent with Newton's third law (see Figure 5).

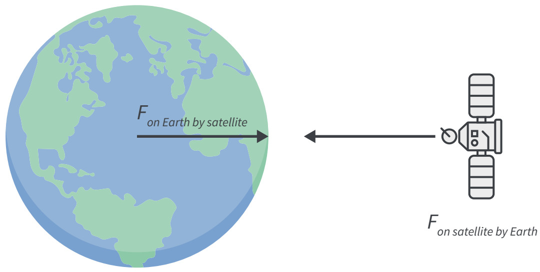


Figure 5 Newton's 3rd law of motion states that for every action there is an equal and opposite reaction. Hence, a satellite orbiting Earth will apply an equal gravitational force on Earth to the force that Earth applies on the satellite.

USEFUL TIP

When calculating gravitational field strength and gravitational force we must use the distance from the centre of the object. Be aware that 'altitude' and 'height' refer to the distance from the surface of the object. If given the altitude, remember to add the radius of the object to this value.

1 Worked example

Use the data table to answer the following questions.

Mass of space station	419 725 kg
Mass of Earth	5.98×10^{24} kg
Radius of Earth	6.37×10^{6} m
Space station's distance from Earth's surface	4.00×10^{5} m
Universal gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a **Calculate the Earth's gravitational field strength at the space station.**

b **Calculate the magnitude of the force due to gravity on the space station by Earth.**

c **Calculate the magnitude of the force due to gravity on Earth by the space station.**

a $g = G\dfrac{M}{r^2}$

Use the Earth's mass, since we are calculating the Earth's gravitational field strength.

Remember to use the distance from the centre of the Earth.

$g = 6.67 \times 10^{-11} \times \dfrac{5.98 \times 10^{24}}{(6.37 \times 10^{6} + 4.0 \times 10^{5})^2}$

$g = 8.70$ N kg^{-1} or m s^{-2}

b $F = mg$

This time we need to use the space station's mass since we are calculating the force on the space station due to Earth's gravitational field (which is $g = 8.7$ N kg^{-1} from part **a**).

$F = 419\ 725 \times 8.7$

$F = 3.7 \times 10^{6}$ N

OR

Use Newton's law of universal gravitation.

$F = G\dfrac{M_1 M_2}{r^2}$

$F = 6.67 \times 10^{-11} \times \dfrac{5.98 \times 10^{24} \times 419\ 725}{(6.37 \times 10^{6} + 4.0 \times 10^{5})^2}$

$F = 3.7 \times 10^{6}$ N

c Using Newton's 3rd law: $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$

That is, the magnitude of the force on Earth by the space station is equal to the magnitude of the force on the space station by Earth.

$F_{on\ Earth\ by\ space\ staion} = 3.7 \times 10^{6}$ N

The inverse square law 3.1.3.1

OVERVIEW

The strength of a gravitational field decreases with the square of the distance from the body creating the field. The inverse square law is useful when we do not actually know the mass of the object creating the field, but we do know the gravitational field strength at one location and want to know the field strength at another location.

THEORY DETAILS

Due to the relationship between gravitational field strength (g) and distance, we get an inverse square law: $g \propto \frac{1}{r^2}$. It states that the strength of the field will decrease as the distance increases with a squared relationship. For example, if the distance from the centre of a planet doubles, the gravitational field strength due to that planet becomes four times smaller. The inverse square law is useful for relating the field strength due to the same object at two different locations. For this reason, the following formula can be a helpful way of representing the inverse square law.

$$g_2 = \frac{g_1}{n^2}$$

g_2= gravitational field strength at position 2 (N kg^{-1}), g_1= gravitational field strength at position 1 (N kg^{-1}), n = the ratio of the distance at position 2 to the distance at position 1 $\left(\frac{r_2}{r_1}\right)$

Assuming the mass of the object 'experiencing' the gravitational field is constant, then the inverse square law applies to gravitational force as well as field strength.

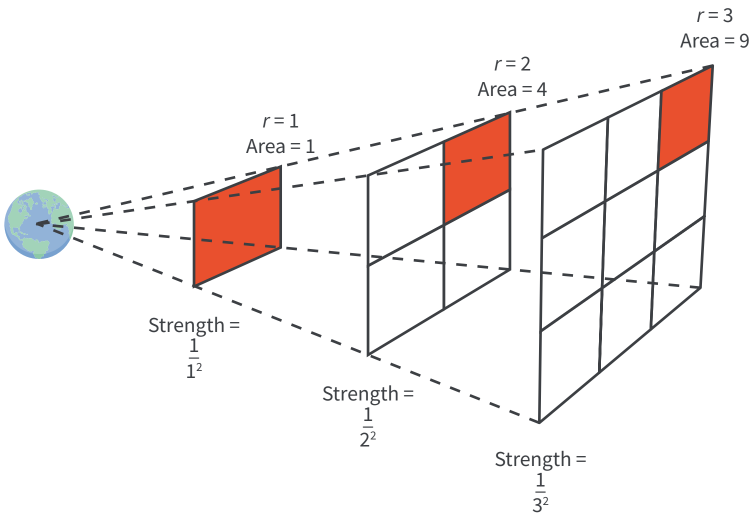


Figure 6 The strength of gravity decreases with the square of the distance from the body.

2 **Worked example**

A satellite experiences a gravitational field strength of 2.0 N kg^{-1}. What would be the value of the gravitational field strength if the satellite was moved to a distance three times its original distance from the centre of the planet?

g_1 = 2.0 N kg^{-1}

Three times the original distance means n = 3

$$g_2 = \frac{g_1}{n^2}$$

$$g_2 = \frac{g_1}{3^2} = \frac{2.0}{9} = 0.22 \text{ N kg}^{-1}$$

The normal force in gravitational fields 3.1.9.2

OVERVIEW

We do not directly **feel** gravity. Instead we feel normal forces which give us a sense of gravity. When an object is in free fall and without air resistance, gravity is the only force acting and hence all objects fall at the same rate.

THEORY DETAILS

If the gravitational force is the only force acting on an object ($F_g = F_{net}$) then $mg = ma$ which means that $g = a$ (gravitational field strength and acceleration are equivalent). For this reason g is also known as the **acceleration due to gravity** and m s^{-2} is considered an equivalent unit to N kg^{-1}. If no other forces such as air resistance are acting, all objects will fall at the same rate regardless of their mass. This was shown on the Moon when David Scott dropped a feather and a hammer at the same time. Both objects fell at the same rate and landed at the same time.

It is a common misconception that gravity does not act on astronauts in orbit. In fact the gravitational field strength at the International Space Station is approximately 90% of the gravitational field strength on Earth. However, astronauts do not **feel** gravity acting on them because gravity is the **only** force (constantly) acting on them and they experience **zero normal force**. As a satellite orbits Earth, it is in free fall with everything inside accelerating at the same rate so objects do not appear to fall relative to the satellite.

USEFUL TIP

The terms 'weight' and 'weightlessness' have been removed from the VCE Physics study design and replaced with 'force due to gravity'. Similarly, 'apparent weightlessness' will not be recognised. Instead it is important to use 'zero normal force' to describe apparent weightlessness.

Theory summary

- A field is a region in which each point is subject to a non-contact force.
  - All objects with mass create their own gravitational field.
  - The strength and direction of a field is represented with field lines.
- The gravitational field strength can be calculated using $g = G\frac{M}{r^2}$.
  - When there are no other forces acting on an object, the gravitational field strength at an object's position is equivalent to acceleration due to gravity ($g = a$).
  - Gravitational field strength can be measured in N kg^{-1} or m s^{-2}.
  - The relationship between the gravitational field strength at two points can be found using the inverse square law without knowing the mass of the body creating the gravitational field.
- The force due to gravity on an object can be calculated using $F = mg$ or $F = G\frac{M_1 M_2}{r^2}$.
- Whilst in orbit astronauts are in free fall so will experience zero normal force.
  - This is why astronauts appear to 'float' in space.

KEEN TO INVESTIGATE?

PhET 'Gravity and Orbits' simulation
https://phet.colorado.edu/en/simulation/gravity-and-orbits

YouTube video: BBC – Brian Cox Visits the World's Biggest Vacuum Chamber
https://youtu.be/E43-CfukEgs

YouTube video: NASA Video – Apollo 15 Proves Galileo Correct
https://youtu.be/ZVfhztmK9zI

YouTube video: The Royal Institution – What is Weightlessness?
https://youtu.be/ysdglvr7s7E

YouTube video: Veritasium – Misconceptions about Falling Objects
https://youtu.be/_mCC-68LyZM

5A Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following statements is false?

A All objects with mass create gravitational fields.

B Gravity is always repulsive.

C Acceleration due to gravity is the same for all objects within a uniform gravitational field.

D Gravity is a non-contact force.

Question 2

Which of the following is **not** a convention for drawing field lines?

A Field lines have a vector nature with both a magnitude and a direction.

B All lines have arrows to indicate the direction of the field.

C Field lines can touch.

D Field lines closer together indicate a greater magnitude.

Question 3

Which of the following units could be used to measure gravitational field strength?

A $N\ s^{-1}$

B $N\ m^{-1}$

C $m\ s^{-1}$

D $m\ s^{-2}$

Use the following information to answer Questions 4–7.

Question 4

Which of the following statements must be true?

A The **gravitational force** on the astronaut by Earth is $\frac{1}{4}$ the Earth's gravitational force on the satellite.

B The **gravitational force** on the astronaut by Earth is $\frac{1}{16}$ the Earth's gravitational force on the satellite.

C The **gravitational field strength** due to Earth at the position of the astronaut is $\frac{1}{16}$ the gravitational field strength at the position of the satellite.

D We must know the mass of all three objects to compare the gravitational field strength of Earth on the astronaut and the satellite.

Question 5

Identify the mass or masses (satellite's mass, Earth's mass, and/or astronaut's mass) that must be used to calculate the **gravitational field strength** of Earth acting on the astronaut.

Question 6

Identify the mass or masses (satellite's mass, Earth's mass, and/or astronaut's mass) that must be used to calculate the **gravitational field strength** of the astronaut acting on the Earth.

Question 7

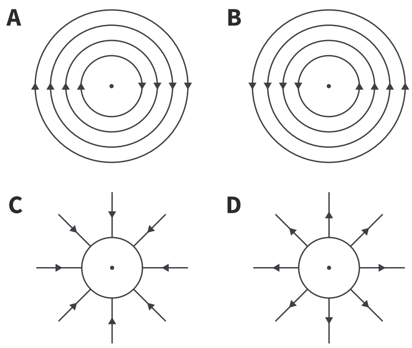
Identify the mass or masses (satellite's mass, Earth's mass, and/or astronaut's mass) that must be used to calculate the **gravitational force** of the astronaut acting on the Earth.

EXAM-STYLE QUESTIONS

This lesson

Question 8 (1 MARK)

Which of the following best represents the gravitational field around a planet?



Question 9 (4 MARKS)

A spacecraft has a mass of 480 kg. It is orbiting Earth at a radius of 7.00×10^{6} m from its centre. Earth has a mass of 5.98×10^{24} kg. Take $G = 6.67 \times 10^{-11}\ N\ m^2\ kg^{-2}$.

a Calculate the magnitude of the force that the spacecraft exerts on Earth. (2 MARKS)

b Calculate the magnitude of the acceleration due to the gravity of Earth on the spacecraft. (2 MARKS)

Question 10 (3 MARKS)

Bob states that astronauts appear to have a 'zero gravity experience' because there is no gravity just outside a planet's atmosphere. Evaluate this statement.

Adapted from 2016 VCAA Exam Section A Q6b

Question 11 (2 MARKS)

The gravitational force on a satellite by a planet is 50 N. The satellite has a mass of 250 kg and it is a distance 4.0×10^{6} m from the centre of the planet. Calculate the mass of the planet. Take $G = 6.67 \times 10^{-11}\ N\ m^2\ kg^{-2}$.

Question 12 (3 MARKS)

Mariner 10 is orbiting Mercury. In its first orbit, it experiences a gravitational field strength of 0.80 N kg^{-1}. Over two years, Mariner 10 changes the altitude of its orbit. At its new altitude, the gravitational field strength is 0.089 N kg^{-1}.

a Did Mariner 10 increase or decrease in altitude? (1 MARK)

b By what factor did Mariner 10 change its distance from the centre of Mercury? Give your answer to the nearest integer (whole number). (2 MARKS)

Question 13 (7 MARKS)

In 2003 the European Space Agency (ESA) launched a space probe to study Mars. The probe is currently in orbit around Mars. Assume the probe maintains the same distance from the planet's centre.

Mass of Mars	6.39×10^{23} kg
Mass of space probe	1.12×10^{3} kg
Radius of Mars	3.39×10^{6} m
Altitude of space probe's orbit	3.0×10^{5} m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a Calculate the magnitude of the acceleration due to gravity that the probe experiences. (2 MARKS)

b Calculate the magnitude of the force due to gravity acting on the probe. (2 MARKS)

c Draw a field diagram to show the gravitational field around Mars. (1 MARK)

d Calculate the magnitude of the gravitational force someone with a mass of 80 kg would experience on the surface of Mars. (2 MARKS)

Previous lessons

Question 14 (6 MARKS)

Scruffy the dog is riding a motorbike zooming down the street at 56 m s^{-1} and crashes into a bus travelling in the same direction moving at the speed limit of 8.3 m s^{-1}. After the collision Scruffy and the motorbike travels backwards at 5.0 m s^{-1}. Scruffy and his motorbike have a combined mass of 340 kg. The bus has a mass of 15 000 kg.

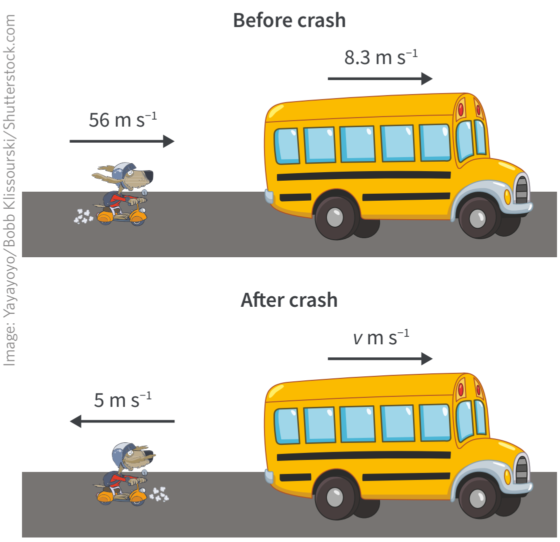


Image: Yayayoyo/Bobb Klissourski/Shutterstock.com

a What is the velocity, v, of the bus after the collision? (3 MARKS)

b Was the collision elastic or inelastic? Support your answer with calculations. (3 MARKS)

Question 15 (3 MARKS)

A spacecraft has a mass of 1500 kg and a relativistic kinetic energy of 5.434×10^{20} J. What is the magnitude of the velocity of the spacecraft? Give your answer in m s^{-1}.

Key science skills

Question 16 (8 MARKS)

Measurements of the Moon's gravitational field strength at a range of distances are shown in the table. Assume there is an uncertainty of 0.05 N kg^{-1} in the measurements of gravitational field strength. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Distance from centre of Moon (10^3 km)	Gravitational field strength (N kg^{-1})
1.80	1.5
2.50	0.8
3.40	0.4
5.60	0.2
8.20	0.1

a Plot the data from the table with distance on the horizontal axis and gravitational field strength on the vertical axis. Ensure you include:

- scales and units on each axis
- uncertainty bars for the gravitational field strength
- a smooth curve of best fit

(5 MARKS)

Adapted from 2017 VCAA Exam Section B Q9b

b Calculate the maximum possible mass of the Moon, considering the uncertainty in the measurements, using the gravitational field strength recorded at 1.8×10^3 km. (3 MARKS)

5B GRAVITATIONAL POTENTIAL ENERGY IN NON-UNIFORM FIELDS

In lesson 3D we learned to calculate the change in gravitational potential energy as an object moved between two points where the gravitational field strength could be treated as constant. In lesson 5A we learned that gravitational field strength cannot be treated as constant over large distances. This lesson will show how we can use gravitational force-distance and gravitational field-distance graphs to calculate the change in gravitational potential energy for an object moving in space where the gravitational field is not constant.

5A Gravitational fields and forces	5B GPE in non-uniform fields	5C Orbital motion

Study design key knowledge dot points

- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
  - the change in gravitational potential energy from area under a force-distance graph and area under a field-distance graph multiplied by mass.

Key knowledge units

Calculating change in GPE from the area under graphs	3.1.3.2 & 3.1.8.2

Formulas for this lesson

Previous lessons		New formulas
2B	$F_g = mg$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Calculating change in gravitational potential energy from the area under graphs 3.1.3.2 & 3.1.8.2

OVERVIEW

For an object that moves large enough distances such that the gravitational field cannot be treated as uniform, the area under a gravitational force-distance graph represents the change in gravitational potential energy. Similarly, the change in gravitational potential energy can be calculated from the area under a field-distance graph multiplied by the mass of the object which is moving through the field.

THEORY DETAILS

Interpretation of the force-distance graph

A gravitational force-distance graph (see Figure 1) represents the magnitude of the force that an object with a particular mass would experience at a given distance from the centre of another body which is creating a gravitational field. The graph is described by the relationship $F = G\frac{M_1 M_2}{r^2}$.

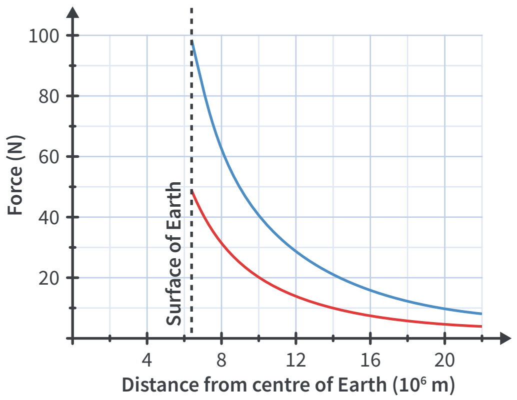


Figure 1 The gravitational force-distance graphs for a 5 kg object (red) and a 10 kg object (blue) due to the Earth's gravitational field. The shape of the force-distance graph will look similar for an object of any mass, however we see that the magnitude of the force is different.

Calculating work and change in gravitational potential energy

When the force due to gravity is the only force acting on an object, work done, ΔGPE, and ΔKE are equal in magnitude. This is because the gravitational potential energy transforms into kinetic energy as an object falls according to the law of conservation of energy ($\Delta KE = -\Delta GPE$).

ΔGPE is found as the **area under a force-distance graph between two radii**, which we can approximate by **counting squares**.

ΔGPE = area under the gravitational **force**-distance graph

In Figure 2, an area under the force-distance graph is shaded which represents the magnitude of the work done by gravity on a 10 kg object moving between 9×10^6 m and 15×10^6 m from Earth's centre.

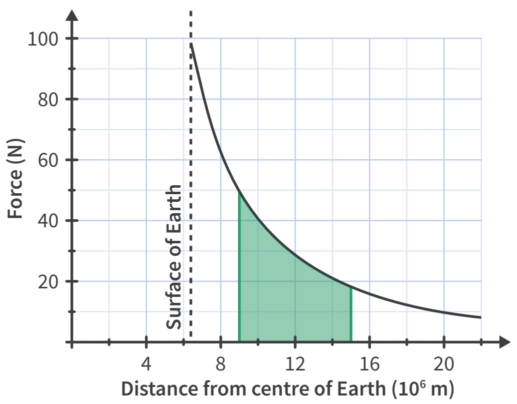


Figure 2 Force-distance graph from the centre of the Earth for a 10 kg mass. The area under the graph shaded in green represents the work done by a 10 kg mass as it moves from 9×10^6 m to 15×10^6 m from the centre of the Earth.

Problem solving process: counting squares

Use this technique if the graph includes gridlines and the region under the line is not easily divided into simple triangles and rectangles (i.e. it is a curved line).

1. Count the number of squares under the line.
2. Instead of keeping track of fractions of boxes use the following simple rule:
   - **If more than 50%** of a square is under the line, include the whole square.
   - **If less than 50%** of a square is under the line, exclude the whole square.
3. Calculate the area of one square (if the axes are in SI units then the result is in joules).
4. Multiply the total number of squares by the area (in joules) of one square.
5. The result is the work done by gravity or ΔGPE in joules.

USEFUL TIP

Make sure to convert to SI units (i.e. metres) whenever extracting information from a question. It is common for an exam questions to give distances in km for a force-distance graph.

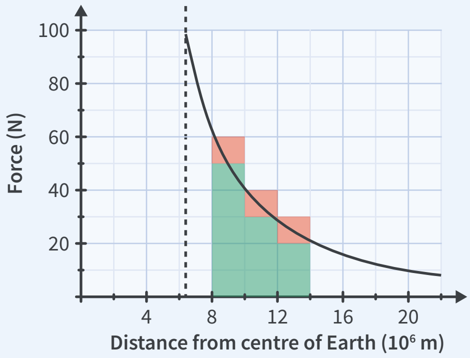
1 Worked example

A 10 kg object is dropped from 14×10^6 m to 8×10^6 m from the centre of the Earth. Take the surface of Earth as zero gravitational potential energy. Use Figure 2 to answer this question.

a **Calculate the magnitude of the change in the gravitational potential energy of the object.**

b **State whether gravitational potential energy increases or decreases as the object falls.**

a Identify the squares which are at least 50% below the line and between the distances of 14×10^6 m and 8×10^6 m.



There are 10 squares under the line. Red squares are excluded as less than half of each square is below the line.

Find the area of a single square.

Area of square = $(2 \times 10^6 \text{ m}) \times (10 \text{ N}) = 2 \times 10^7$ J

Multiply the number of squares by the area of each square.

$\Delta GPE = 10 \times 2 \times 10^7 = 2 \times 10^8$ J

b Gravitational potential energy decreases as the distance from the object to the Earth decreases.

Gravitational field-distance graphs

A gravitational field-distance graph plots the magnitude of the gravitational field strength, g, against the distance from the centre of the object that creates the field. Field-distance graphs are independent of the mass of an object within the field, and only depend on the mass of the gravitational body creating the field.

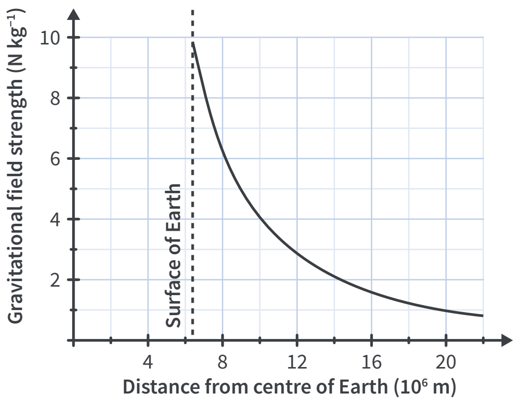


Figure 3 The gravitational field strength versus distance from the centre of the Earth. It looks similar to a gravitational force-distance graph **but the vertical axis is different**.

The gravitational field strength is also the acceleration due to gravity. Notice that the maximum field strength (at the surface of Earth) in Figure 3 is 9.8 N kg^{-1} or 9.8 m s^{-2}.

The gravitational force acting on an object is found by multiplying the mass of the object by the gravitational field strength $\left(F_g = mg\right)$. Similarly, the magnitude of the work done (or ΔGPE or ΔKE) on an object moving through a gravitational field can be calculated by taking the area under the field-distance graph and **multiplying it by the mass** of the object moving through the field.

ΔGPE = area under the gravitational **field**-distance graph × mass

USEFUL TIP

The equation $\Delta GPE = mg_f h_f - mg_i h_i$ (where g_i and g_f have different values that are found from the graph, and h_i and h_f must be measured from the centre of the body) will correctly calculate the change in gravitational potential energy for situations where the field must be treated as non-uniform. However, this method is recommended only for checking your answer, since the VCE Physics Study Design specifies the use of areas under graphs.

2 Worked example

Use the graph from Figure 3 to answer the following questions for a 500 kg space probe.

a **What is the magnitude of the gravitational force acting on the space probe at 16×10^6 m from the centre of the Earth?**

b **The space probe moves from a distance of 16×10^6 m to 22×10^6 m from the centre of the Earth. Calculate the change in gravitational potential energy of the probe.**

a Find the point on the graph where the distance from the centre of the Earth is 16×10^6 m

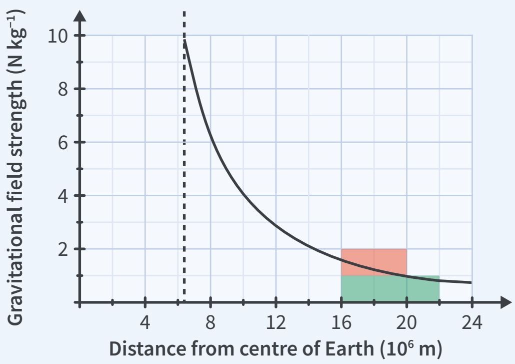
Find the corresponding gravitational field strength on the *y*-axis at that point: $g \approx 1.6$ N kg^{-1}

Use the formula $F_g = mg$ to calculate the force due to gravity.

$F_g = 500 \times 1.6$

$F_g = 8.0 \times 10^2$ N

b Identify the squares which are at least 50% below the line and between the distances of 16×10^6 m and 22×10^6 m.



There are 3 squares under the line (shown in green). Red squares are excluded as less than half of each square is below the line.

Find the area of a single square.

Area of square = $(2 \times 10^6 \text{ m}) \times (1 \text{ N kg}^{-1}) = 2 \times 10^6$ J kg^{-1}

Multiply the number of squares by the area of each square **and by the mass of the satellite**.

$\Delta GPE = 3 \times (2 \times 10^6) \times 500$

$\Delta GPE = 3 \times 10^9$ J

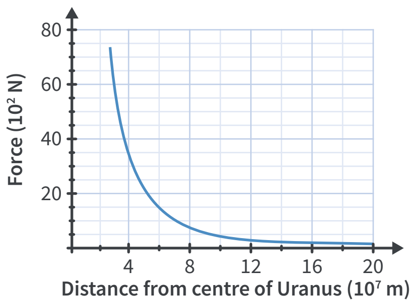
Theory summary

- A gravitational force-distance graph shows the gravitational force on an object with a particular mass versus the distance that the mass is from the centre of another body which is creating a gravitational field.
  - ΔGPE = area under the **force**-distance graph
- A gravitational field-distance graph shows the field strength (acceleration due to gravity) versus the distance from the centre of the body which is creating the field.
  - ΔGPE = area under the **field**-distance graph × **mass**
- When the force due to gravity is the only force involved, the magnitudes of ΔGPE and ΔKE are equal.

5B Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–3.



Question 1

What is the magnitude of the gravitational force at 4×10^7 m from the centre of Uranus?

A 4.2 N

B 4.2×10^2 N

C 35 N

D 3500 N

Question 2

Which option is closest to the number of squares under the graph between 4×10^7 m and 12×10^7 m from the centre of Uranus?

A 4

B 6

C 8

D 10

Question 3

What is the value represented by the area of one square?

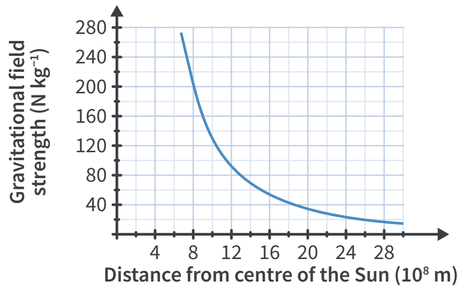
A 1.0 J

B 10 J

C 1.0×10^6 J

D 1.0×10^{10} J

Use the following information to answer Questions 4–7.



Question 4

What is the magnitude of the gravitational acceleration at 8×10^8 m from the centre of the Sun?

A 800 m s^{-2}

B 200 m s^{-2}

C 80 m s^{-2}

D 20 m s^{-2}

Question 5

What is the magnitude of the gravitational force on an object with mass *m* at 18×10^8 m from the centre of the Sun?

A $40 \times m$ N

B 40 N

C 80 N

D 200 N

Question 6

Which option is closest to the number of squares under the graph between 12×10^8 m and 16×10^8 m from the centre of the Sun?

A 3

B 5

C 7

D 9

Question 7

What is the value represented by the area of one square?

A 40 J kg^{-1}

B 4×10^8 J kg^{-1}

C 4×10^9 J kg^{-1}

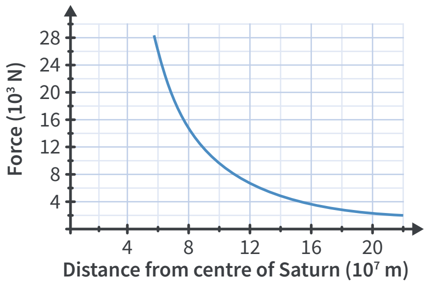
D 4×10^{10} J kg^{-1}

EXAM-STYLE QUESTIONS

This lesson

Question 8 (7 MARKS)

The spacecraft Cassini falls from 16×10^7 m to 8.0×10^7 m from the centre of Saturn. Take Cassini's mass to be 5700 kg. A graph is used to show the gravitational force experienced by Cassini against distance from the centre of Saturn.



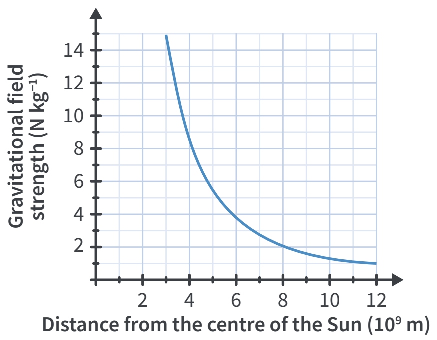
a Calculate the work done by gravity on Cassini when it moves from a distance of 16×10^7 m to 8.0×10^7 m from the centre of Saturn. Show your working. (3 MARKS)

b Will the gravitational potential energy of Cassini increase, decrease, or not change as it falls closer to Saturn? Justify your answer. (2 MARKS)

c What is the magnitude of the gravitational acceleration of Cassini at a distance of 8.0×10^7 m from the centre of Saturn? (2 MARKS)

Question 9 (5 MARKS)

The Parker Solar Probe was launched in 2018 to study the Sun. It will do this by flying closer to the Sun than any other spacecraft before. Assume the probe has a mass of 555 kg.

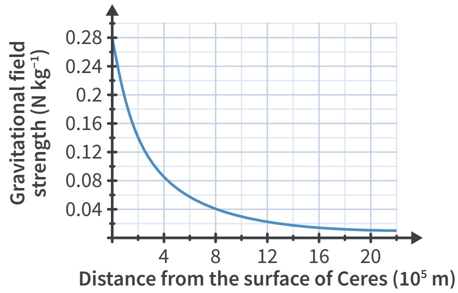


a Use the graph to calculate the change in gravitational potential energy as the Parker Solar Probe moves between the distances of 7.0×10^9 m and 11.0×10^9 m from the centre of the Sun. (3 MARKS)

b Use the graph to find the magnitude of the gravitational force that the Parker Solar Probe experiences at a distance of 8.0×10^6 km from the centre of the Sun. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q9

Question 10 (5 MARKS)



a A 500 kg object falls from 22×10^5 m onto the surface of Ceres. Calculate the amount of kinetic energy the object gains. (3 MARKS)

b Assuming that the object begins with a speed of 50.0 m s^{-1}, use your answer from part **a** to determine the speed at which the object will impact Ceres. (2 MARKS)

Previous lessons

Question 11 (4 MARKS)

The gravitational field strength on the surface of Europa is 1.214 N kg^{-1}. The 252 kg Europa Clipper lander-craft is dropped vertically 10.0 m from rest onto the surface of Europa.

a Determine the work done by gravity on the lander-craft as it fell to the surface. (2 MARKS)

b Calculate the kinetic energy of Europa Clipper when it is 5.00 m from the surface. (2 MARKS)

Question 12 (3 MARKS)

A 10 000 kg spacecraft is travelling at 95% the speed of light when measured in the Earth's reference frame. Calculate the total energy of the spacecraft when measured in the Earth's reference frame.

Key science skills

Question 13 (5 MARKS)

Al and Kat both gather data on the gravitational field strength of Earth at different distances from the Earth's centre.

Distance from the centre of the Earth (m)	Gravitational field strength as measured by Al (N kg^{-1})	Gravitational field strength as measured by Kat (N kg^{-1})	True value of the gravitational field strength (N kg^{-1})
6.4×10^6	9.6	9.8	9.8
9.9×10^6	3.7	4.1	4.1
13.4×10^6	1.8	2.3	2.2
16.9×10^6	1.1	1.5	1.4
20.4×10^6	0.6	0.8	1.0

a Plot Kat's data on a graph. (3 MARKS)

b Determine who gathered the most accurate data. Justify your answer. (2 MARKS)

5C ORBITAL MOTION

Isacc Newton once said, ‘I can calculate the motion of heavenly bodies, but not the madness of people.’ This lesson will build upon what we learned about gravitational fields, forces, and acceleration introduced in lessons 5A and 5B. It will combine that knowledge with our understanding of circular motion from chapter 2 in order to introduce the mathematics necessary to describe the orbital motion of satellites.

5A Gravitational fields and forces	5B GPE in non-uniform fields	5C Orbital motion

Study design key knowledge dot points

- apply the concepts of force due to gravity, F_g, and normal reaction force, F_N, including satellites in orbit where the orbits are assumed to be uniform and circular
- model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$

Key knowledge units

The force on an object in orbit	3.1.9.1
Orbital radius, period, and speed	3.1.10.1

Formulas for this lesson

Previous lessons		New formulas
2D	* $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$	$4\pi^2 r^3 = GMT^2$
2D	$v = \frac{2\pi r}{T}$	$v = \sqrt{\frac{GM}{r}}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

orbit a periodic circular or elliptical path that an object takes around another

satellite any object that gravitationally orbits another body, such as a planet or star

The force on an object in orbit 3.1.9.1

OVERVIEW

Gravity provides the only force acting on an object in orbit. Any object in orbit, known as a satellite, is constantly falling towards the body around which it is orbiting. The satellite can be considered to be constantly ‘missing’ the body due to the component of its velocity pointing perpendicular to the gravitational field. In VCE Physics we model orbits as uniform circular motion, where the gravitational force is the centripetal force which acts radially inwards.

THEORY DETAILS

Isaac Newton was a key figure in developing the ideas for orbital mechanics. In order to understand what an orbit was he came up with a thought experiment (see Figure 1). He imagined a cannon on the highest mountain on Earth, where the cannon would fire cannon balls horizontally at ever-increasing speeds.

If the cannonball is:

- launched at a speed which is too slow, the ball will hit the ground.
- launched at a speed which is too fast, the ball will make an elliptical path or 'escape' the Earth's gravitational field.
- launched at just the right speed (known as orbital speed), the ball will continuously fall towards the Earth without ever getting closer to the ground due to the curvature of the Earth. Hence, ignoring air resistance, the ball would never touch the ground and circle around the Earth forever at a constant radius from its centre.

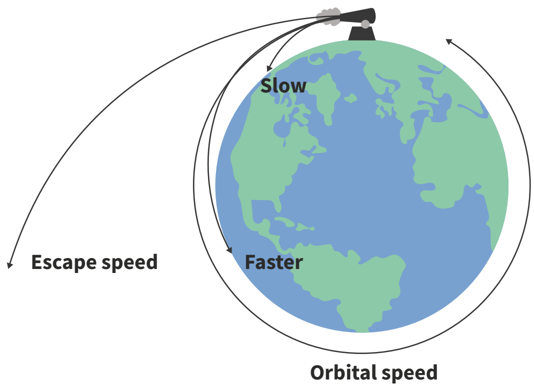


Figure 1 Isaac Newton's thought experiment of a cannon firing a cannonball around Earth

The force due to gravity is the only force acting on a satellite ($F_{net} = F_g$). In lesson 2D we learned that for an object moving in a circular path, the net force is the centripetal force and it always acts radially inwards (towards the centre of the circle). When we model a satellite undergoing uniform circular orbital motion (as is always the case in VCE Physics), the force due to gravity is the centripetal force ($F_g = \frac{mv^2}{r}$).

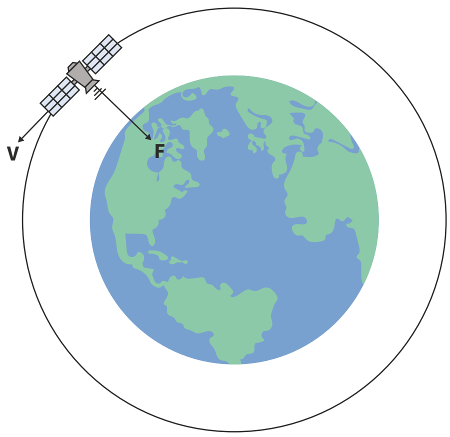


Figure 2 A satellite orbiting Earth. Its force vector points towards the centre of the Earth, while its velocity vector points tangentially along its circular path.

Orbital radius, period, and speed 3.1.10.1

OVERVIEW

The laws of orbital motion can be used to calculate the radius, period, and speed of a circular orbit. For a given orbital radius around a central body of a given mass, there is only one allowable orbital period and hence only one allowable orbital speed.

THEORY DETAILS

Since we model orbital motion as following a circular path, we can equate the magnitude of the acceleration due to gravity ($g = G\frac{M}{r^2}$) to the formulas for centripetal acceleration.

Given that the magnitude of centripetal acceleration can be calculated by $a = \frac{v^2}{r}$, for uniform circular orbital motion we have: $G\frac{M}{r^2} = \frac{v^2}{r}$

This can be rearranged to give the orbital speed of a satellite.

$$v = \sqrt{\frac{GM}{r}}$$

v = orbital speed (m s^{-1}), G = gravitational constant (6.67×10^{-11} N m^2 kg^{-2}), M = mass of body being orbited (kg), r = radius of orbit (m)

Note that the mass of the object which is in orbit **does not** affect the orbital speed.

1 **Worked example**

Data for a spacecraft orbiting the Earth

Mass of Earth	5.98×10^{24} kg
Orbital radius	2.28×10^{7} m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Calculate the speed of the spacecraft.

Use the equation: $v = \sqrt{\frac{GM}{r}}$

Substitute from the table into the equation: $v = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{2.28 \times 10^{7}}}$

Solve: $v = 4.18 \times 10^{3}$ m s^{-1}

Using an alternative formula for centripetal acceleration, $a = \frac{4\pi^2 r}{T^2}$, we can establish another relationship for uniform circular orbital motion: $\frac{4\pi^2 r}{T^2} = G\frac{M}{r^2}$

When rearranged and simplified this gives us:

$$4\pi^2 r^3 = GMT^2$$

r = radius of orbit (m), G = gravitational constant (6.67×10^{-11} N m^2 kg^{-2}), M = mass of object being orbited (kg), T = orbital period (s)

USEFUL TIP

The equations of orbital motion are long and often involve large numbers. Completing the calculation twice or backwards checking your answer on your calculator will reduce the likelihood of an error.

We can rearrange this equation to find r, M, and T:

$r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$, $M = \frac{4\pi^2 r^3}{GT^2}$, $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$

Note that the mass of the object which is in orbit **does not** affect the orbital radius or period.

USEFUL TIP

It is common for exams to ask a question which requires the relationship between orbital period and orbital radius, but it is not included on the VCE Physics Formula Sheet. It can be helpful to copy into your pre-written notes the transformed equations giving the radius, mass, period, and orbital speed.

There are some important points to emphasise here.

- A satellite's orbital radius, period and speed are all independent of its mass.
- If a satellite's orbital radius increases, its period will also increase while its speed will decrease.
  - Using the equation $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$, we can see that $T \propto \sqrt{r^3}$, which means T increases as r increases.
  - Using the equation $v = \sqrt{\frac{GM}{r}}$, we can see that $v \propto \frac{1}{\sqrt{r}}$, which means v decreases as r increases.
- The orbital radius is measured from the centre of the orbiting object to the **centre** of the object being orbited.

2 **Worked example**

Data for Jupiter's moon, Europa

Orbital period of Europa	3.08×10^5 s
Orbital radius	6.71×10^8 m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a **Calculate the speed of Europa's orbit.**

b **Use the data about Europa's orbit to calculate the mass of Jupiter.**

a Use the equation: $v = \frac{2\pi r}{T}$

Substitute the orbital radius and speed from the table into the equation

$1.37 \times 10^4 = \frac{2 \times \pi \times 6.71 \times 10^8}{3.08 \times 10^5} = \frac{4.22 \times 10^9}{3.08 \times 10^5}$

$v = 1.37 \times 10^4$ m s^{-1}

b Use the equation: $4\pi^2 r^3 = GMT^2$

Substitute the orbital radius, orbital period and gravitational constant into the equation:

$4 \times \pi^2 \times (6.71 \times 10^8)^3 = 6.67 \times 10^{-11} \times M \times (3.08 \times 10^5)^2$

$1.19 \times 10^{28} = 6.33 \times M$

Transpose the equation to make M the subject: $M = \frac{1.19 \times 10^{28}}{6.33}$

$M = 1.88 \times 10^{27}$ kg

Geostationary orbits

A geostationary orbit is a special case where a satellite will remain at the same location relative to the Earth's surface. The conditions for this to occur are:

- The period of the orbit must equal the period of rotation of the Earth (that is, the duration of one day).
- The satellite must orbit directly above the equator and in the same direction as Earth's rotation.

Theory summary

- For uniform circular orbital motion of a satellite, the force due to gravity is the centripetal force. It is the only force acting on the satellite.
- There is only one possible period (and speed) for an orbit at a given radius around a given body.
- Speed, mass, and radius are related by $v = \sqrt{\frac{GM}{r}}$.
- Speed, radius, and period are related by $v = \frac{2\pi r}{T}$.
- Mass, radius, and period are related by $4\pi^2 r^3 = GMT^2$.

KEEN TO INVESTIGATE?

YouTube video: Scott Manley – Geostationary, Molniya, Tundra, Polar & Sun Synchronous Orbits Explained
https://youtu.be/PZAkiXNJIqc

YouTube video: Veritasium – Why Are Astronauts Weightless?
https://youtu.be/iQOHRKKNNLQ

Weber, Newton's Cannon
https://physics.weber.edu/schroeder/software/NewtonsCannon.html

5C Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following statements is **false**?

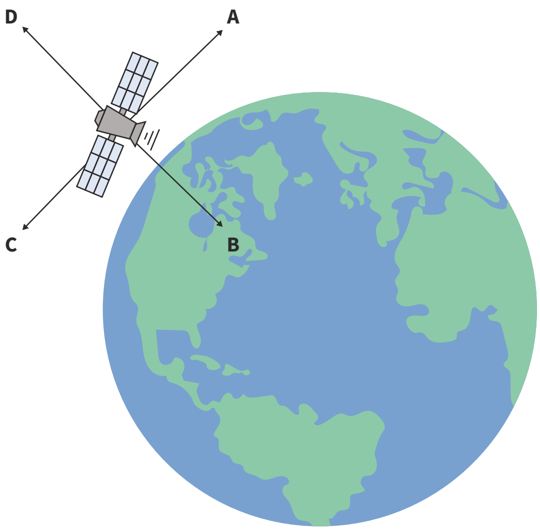
A The force due to gravity and velocity vectors of a satellite in a circular orbit are always perpendicular.

B The force due to gravity on a satellite undertaking circular orbital motion acts radially inwards.

C A satellite's velocity is in the direction of the gravitational force acting upon it.

D The velocity of a satellite in orbit is always perpendicular to its acceleration.

Use the following information to answer Questions 2 and 3.



Question 2

Using the given diagram, what is the direction of the force on the satellite by the Earth?

Question 3

Assuming the satellite is in a circular orbit, which option(s) could represent the direction of the satellite's velocity?

Question 4

A satellite orbiting a star increases its orbital radius. Which of the following gives the change in orbital speed and period?

	Speed	Period
A	Increase	Decrease
B	Decrease	Increase
C	Increase	Increase
D	Decrease	Decrease

Question 5

A satellite changes from a high speed orbit to a lower speed orbit. Which of the following gives the change in orbital radius and period?

	Radius	Period
A	Increase	Decrease
B	Decrease	Increase
C	Increase	Increase
D	Decrease	Decrease

Question 6

Two satellites are in orbits with the same radius around the same planet. Satellite 1 has a greater mass than satellite 2. Which of the following describes the orbital speed and period of satellite 1 compared to satellite 2?

	Speed	Period
A	Greater	Shorter
B	Lower	Greater
C	Greater	Greater
D	The same	The same

Question 7

If we are given the mass of a planet and the orbital period of a satellite, which formula would be best to calculate the satellite's orbital radius?

A $v = \sqrt{\frac{GM}{r}}$

B $v = \frac{2\pi r}{T}$

C $4\pi^2 r^3 = GMT^2$

D $a = \frac{4\pi^2 r}{T^2}$

EXAM-STYLE QUESTIONS

This lesson

Question 8 (1 MARK)

A satellite is in "Saturn-stationary" orbit (maintaining a fixed position relative to Saturn's surface). Given that a day on Saturn is 10 hours, 41 minutes and 57 seconds, determine the orbital period of the satellite in seconds.

Question 9 (3 MARKS)

Mass of Moon	7.35×10^{22} kg
Mass of Earth	5.98×10^{24} kg
Radius of Earth	6.37×10^{6} m
Orbital period of the Moon	2.376×10^{6} s
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Use the data to calculate the distance from the centre of the Moon to the Earth's surface.

Question 10 (3 MARKS)

Alistair, Zev and Georgina are on a spaceship orbiting the Earth and want to increase the radius of their orbit.

Alistair states that if they lower the mass of the spacecraft, the orbital radius will increase.

Zev states that lowering the mass of the spacecraft will decrease the orbital radius.

Georgina states that the orbital radius would stay the same.

Evaluate the three statements. Detailed calculations are **not** necessary but you need to support your answer.

Adapted from 2017 VCAA Exam Section B Q4c

Question 11 (6 MARKS)

The table provides data for the Earth's orbit around the Sun.

Mass of Sun	1.99×10^{30} kg
Mass of Earth	5.98×10^{24} kg
Period of Earth's orbit	365 days
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a Calculate the radius of Earth's orbit around the Sun. Show your working out. (4 MARKS)

b What is the orbital speed of Earth around the Sun? (2 MARKS)

Question 12 (3 MARKS)

The table provides data for Triton which is a moon of Neptune.

Mass of Triton	2.14×10^{22} kg
Period of Triton's orbit	5.08×10^{5} s
Radius of Triton's orbit	3.55×10^{8} m

Use the data to calculate the mass of Neptune. Show your working out.

Question 13 (3 MARKS)

NASA mission control decides to lower the orbit of its satellite Juno around Jupiter. Will this increase, decrease or have no effect on the speed of the satellite's orbit? Justify your answer.

Adapted from 2018 VCAA NHT Exam Section B Q1b

Question 14 (4 MARKS)

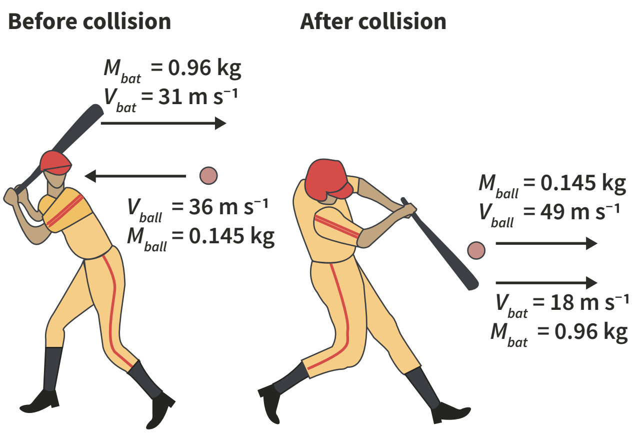
Before landing on the Moon, Apollo 11 orbited 121 km above its surface. Take the mass of the moon to be $M = 7.36 \times 10^{22}$ kg, its radius to be $R_M = 1.74 \times 10^{6}$ m, and take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Calculate how long it took Buzz Aldrin, Micheal Collins, and Neil Armstrong (the crew of Apollo 11) to orbit the Moon once.

Adapted from 2012 VCAA Exam 1 Section A AoS 1 Q8

Previous lessons

Question 15 (3 MARKS)



A game of baseball is being played. The pitcher throws the ball towards the batter at 36 m s^{-1} who swings their bat at 31 m s^{-1}. After hitting the ball, the bat is moving at 18 m s^{-1} and the ball is moving at 49 m s^{-1}. The mass of the bat is 960 g, and the ball 145 g.

Is the collision elastic or inelastic? Justify your answer with calculations.

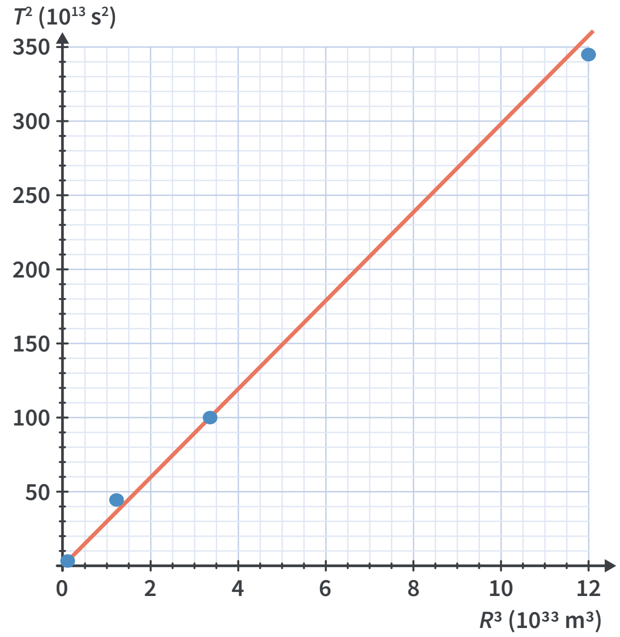
Question 16 (2 MARKS)

The force due to gravity acting on a satellite as it orbits a planet is 500 N. Calculate the magnitude of the force due to gravity acting on the satellite if it doubles the radius of its orbit.

Key science skills

Question 17 (5 MARKS)

Students are measuring the period and radius of planets orbiting the Sun and produce the following graph.



a Calculate the gradient of the line shown. (2 MARKS)

b Use the gradient found in part **a** to determine the mass of the Sun. Show your working. (3 MARKS)

Adapted from 2018 VCAA Exam Section B Q20

CHAPTER 5 QUESTIONS

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 statements is false?

A Gravity is always attractive.

B Gravity acts only on objects within a planet's atmosphere.

C All objects with mass attract all other objects with mass.

D All objects with mass produce their own gravitational field.

Question 2

A spacecraft is orbiting the planet Mercury at a distance R from the centre of the planet. The spacecraft needs to lower its orbit to a distance $\frac{1}{4}R$ from the centre of Mercury. If the initial gravitational force on the spacecraft was 450 N, what is the magnitude of the force on the spacecraft after lowering its orbit?

A 1800 N **B** 112.5 N **C** 7200 N **D** 28.1 N

Question 3

Scientists want to **reduce the period** of a satellite's orbit around a planet. Which of the following statements best describes how this would affect **the orbital radius**?

A The orbital radius will need to decrease.

B The orbital radius will need to increase.

C The orbital radius will not change since the mass of the planet is constant.

D The orbital radius could be any value, depending on the speed of the satellite.

Question 4

Which of the following best describes how **reducing the mass** of a satellite, while keeping its orbital radius constant, will affect its **speed**?

A The speed will decrease.

B The speed will increase.

C The speed will not change since the mass of the planet is constant.

D The speed could be any value, depending on the period of the satellite.

Question 5

Scientists are measuring the magnitude of the force between two steel balls of masses of 100 g and 1000 g, placed 10 mm apart. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Which of the following best gives the gravitational force between the two masses?

A 6.7 N **B** 6.7×10^{-2} N **C** 6.7×10^{-4} N **D** 6.7×10^{-8} N

Adapted from 2017 VCAA Sample Exam Section A Q3

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.

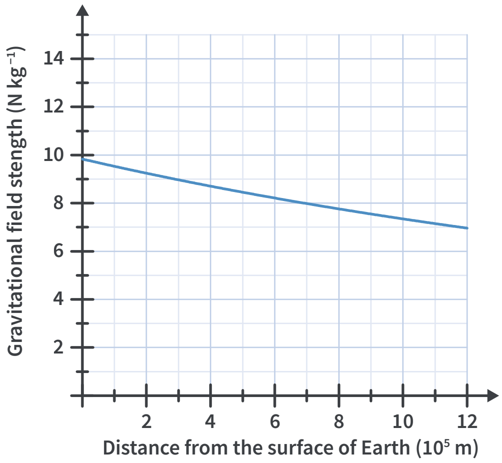
Question 6 (3 MARKS)

A spacecraft called New Horizons was sent to study Pluto. The space probe approached Pluto at 57 936 km h^{-1}. Pluto has a mass of 1.30×10^{22} kg and a radius of 1.19×10^6 m. Show that New Horizons would not be able to orbit Pluto at 57 936 km h^{-1}. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 7 (7 MARKS)

A Falcon 9 rocket has a mass of 4.49×10^5 kg and will launch into an orbit of 5.00×10^5 m above the Earth's surface. Earth has a mass of 5.98×10^{24} kg and a radius of 6.37×10^6 m.

The graph shows the change in gravitational field strength versus the height above the Earth's surface. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.



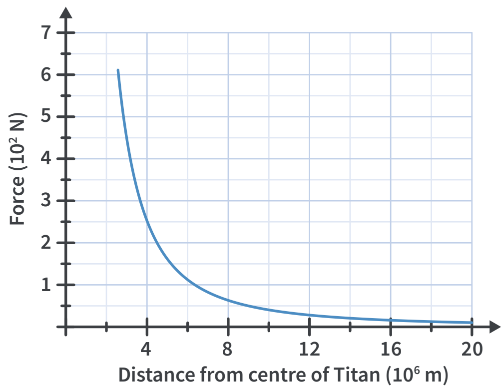
a Use the graph to calculate the change in gravitational potential energy of the Falcon 9 as it moves from the Earth's surface to its orbit at an altitude of 5.00×10^5 m. (3 MARKS)

b Calculate the kinetic energy of the Falcon 9 once it has established a stable orbit at an altitude of 5.00×10^5 m above the surface of Earth. (4 MARKS)

Question 8 (6 MARKS)

Mission Dragonfly is a concept that NASA is pursuing to put a nuclear-powered drone on the surface of Saturn's largest moon, Titan. The table provides information about the Dragonfly drone and Titan. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Mass of Dragonfly	450 kg
Mass of Titan	1.35×10^{23} kg
Radius of Titan	2.57×10^6 m
Radius of Titan including atmosphere	4.00×10^6 m



The graph shows how the gravitational force on Dragonfly changes when it approaches Titan.

a Use the graph to find the acceleration due to gravity that Dragonfly would experience when it is 8.00×10^6 m from the centre of Titan. (2 MARKS)

b Use the graph to estimate the magnitude of the change in kinetic energy as Dragonfly falls from a distance of 12×10^6 m from the centre of Titan to the top of Titan's atmosphere. (2 MARKS)

c Calculate the gravitational field strength on the surface of Titan. (2 MARKS)

Question 9 (4 MARKS)

Astronauts on the International Space Station (ISS) do not feel the effects of gravity.

Mass of Earth	5.98×10^{24} kg
Mass of ISS	420×10^3 kg
Height of the ISS orbit above Earth	400 km
Radius of Earth	6.37×10^6 m

a Calculate the gravitational field strength of the Earth at the ISS. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. (2 MARKS)

b Is the force of gravity on an astronaut at the ISS zero? Explain why astronauts do not feel gravity on the ISS. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q10b

Question 10 (3 MARKS)

An exoplanet has a radius R_X and the gravitational field strength on its surface is 50 N kg^{-1}. Calculate the force due to gravity on a rocket by the exoplanet when the rocket is at a distance $10R_X$ from the centre of the exoplanet. The rocket has a mass of 4.0×10^3 kg.

Question 11 (4 MARKS)

A geostationary orbit is when a satellite remains over a fixed point on the Earth's surface.

a What is the period of a geostationary orbit? Give your answer in seconds. (1 MARK)

b Earth has a radius of 6.37×10^6 m and a mass of 5.98×10^{24} kg. How far above the Earth's surface do geostationary satellites orbit? Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. (3 MARKS)

Question 12 (6 MARKS)

The Pioneer Venus 1 was sent by NASA to study Venus from orbit. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Mass of Venus	4.87×10^{24} kg
Radius of Venus	6051.8 km
Mass of Pioneer Venus 1	517 kg
Period of Pioneer Venus 1 orbit	8.64×10^4 s

a Calculate the gravitational force acting upon Pioneer Venus 1. (4 MARKS)

b Calculate the speed of Pioneer Venus 1's orbit. (2 MARKS)

Question 13 (12 MARKS)

Kepler 22 is a star located 990 light-years from Earth. Scientists have collected data from the five planets orbiting Kepler 22. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Planet	Orbital speed (m s^{-1})	Orbital radius (m)	v^2 (10^{14} m^2 s^{-2})	$\frac{1}{r}$ (10^{-14} m^{-1})
Kepler 22b	1.06×10^8	8×10^{12}	112	12.5
Kepler 22c	8.2×10^7	1.4×10^{13}	67	7.1
Kepler 22d	7.2×10^7	1.8×10^{13}	52	5.6
Kepler 22e	3.8×10^7	6.4×10^{13}	14	1.6
Kepler 22f	2.9×10^7	1.07×10^{14}	8.4	0.935

a Find the orbital period for Kepler 22e. (2 MARKS)

b On a set of axes:

- Plot a graph of the data v^2 (vertical axis) versus $\frac{1}{r}$ (horizontal axis)
- Label the axes with units
- Include a scale on each axis
- Draw a line of best fit

(5 MARKS)

c Calculate the gradient of the line of best fit drawn in part **b**. Include an appropriate unit. (2 MARKS)

d Use the value of the gradient calculated in part **c** to determine the mass of Kepler 22. Show your working. (3 MARKS)

Adapted from 2018 VCAA Exam Section B Q20

BONUS – CARTOON QUESTIONS

Newton's cradle famously exemplifies near-elastic collisions. Using the flip cartoon of the cradle in the corners of the pages of this book, answer the following questions.

Multiple choice questions

Use the following information to answer Questions 1–2.

Apart from their personalities, the spheres of the cradle are identical, and each has a mass of 500 g. The cradle was set in motion by bringing the right sphere to a point 10 cm above its original height, before being let go.

Question 1 (1 MARK)

What was the right sphere's kinetic energy just before it first collided with its neighbouring sphere?

A. 2.5×10^2 J

B. 2.5×10^2 mJ

C. 4.9×10^2 J

D. 4.9×10^2 mJ

Question 2 (1 MARK)

The collision between the right sphere and its neighbour lasted for 5.0 ms. What was the average force that the spheres exerted on each other?

A. 1.4×10^2 N

B. 2.0×10^2 N

C. 9.9×10^1 N

D. 3.5×10^{-3} N

Short answer questions

Question 3 (4 MARKS)

a Given that the right sphere is stationary after the first collision, determine if the collision was elastic. Explain your answer. (3 MARKS)

b Did the left sphere achieve the same maximum height as the right sphere? (1 MARK)

Question 4 (2 MARKS)

When the left sphere reached its maximum height, it was 15 cm away from its neighbour. Calculate the gravitational force that these two spheres exerted on each other at this point.

UNIT 3 AOS 1, CHAPTER 6

Electric and magnetic fields

06

6A Electric fields

6B Magnetic fields

6C Magnetic forces on charged particles

6D DC motors

Key knowledge

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- investigate and apply theoretically and practically a vector field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of an electric field to accelerate a charge, including:
  - electric field and electric force concepts: $E = k\frac{Q}{r^2}$ and $F = k\frac{q_1 q_2}{r^2}$
  - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
  - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$
- analyse the use of a magnetic field to change the path of a charged particle, including:
  - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel
  - the radius of the path followed by a low-velocity electron in a magnetic field: $qvB = \frac{mv^2}{r}$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other
- investigate and analyse theoretically and practically the force on a current carrying conductor due to an external magnetic field, $F = nILB$, where the directions of I and B are either perpendicular or parallel to each other
- investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator
- model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field)

Image: Marc Ward/Shutterstock.com

6A ELECTRIC FIELDS

This lesson will expand our understanding of the field model introduced in chapter 5 to include electric fields. Every object with an electric charge creates an electric field. We will learn to draw electric fields and calculate electrical field strength, forces, and potential energy changes in uniform and non-uniform electric fields.

6A Electric fields	6B Magnetic fields	6C Magnetic forces on charged particles	6D DC motors

Study design key knowledge dot points

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of an electric field to accelerate a charge, including:
  - electric field and electric force concepts: $E = k\frac{Q}{r^2}$ and $F = k\frac{q_1 q_2}{r^2}$
  - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
  - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other
- model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field)

Key knowledge units

Electric fields around point charges	3.1.2.1.4 & 3.1.2.2 & 3.1.6.1 & 3.1.11.1
Electric fields between charged plates	3.1.2.1.5 & 3.1.6.2 & 3.1.14.1

Formulas for this lesson

Previous lessons		New formulas
3B	$W = Fs$	* $E = \frac{V}{d}$
		* $E = \frac{kq}{r^2}$
		* $F = qE$
		* $F = \frac{kq_1 q_2}{r^2}$
		$W = qV = qEd$
		* $\frac{1}{2}mv^2 = qV$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

charge a quantifiable property which relates to how strongly an object is affected by an electric field

electric field strength a measure of the electric force that acts per unit of charge at a point in space

Electric fields around point charges 3.1.2.1.4 & 3.1.2.2 & 3.1.6.1 & 3.1.11.1

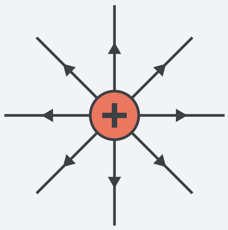
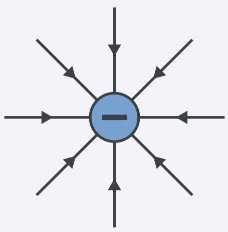
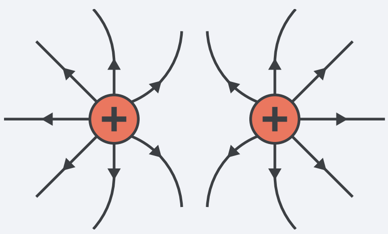
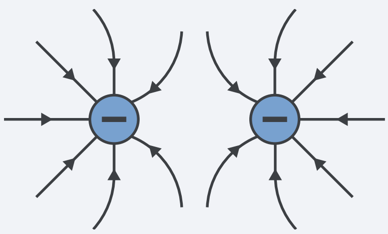
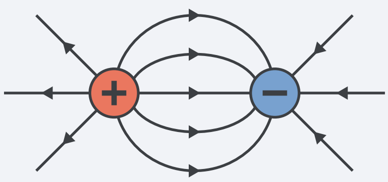
OVERVIEW

Electric fields are produced by electric charges, and can be modelled by drawing field line diagrams. We can calculate the magnitude of the force on a charge in an electric field by using Coulomb's law.

THEORY DETAILS

Electric field lines are used to visualise the nature of electric fields over a region of space. Field lines always start and/or end at a charge – they point away from positive charges and towards negative charges. The field lines represent the direction of the force that a positive charge will experience at that location. In VCE Physics we will need to know how to draw field lines generated by up to two electric charges.

Table 1 Electric field patterns around point charges.

(a) 	**A single positive charge** Field lines point radially outwards, away from the positive charge. Field lines are drawn equally spaced around the charge.
(b) 	**A single negative charge** Field lines point radially inwards, towards the negative charge. Field lines are drawn equally spaced around the charge.
(c) 	**Two positive charges** Field lines point away from the positive charges. Field lines bend away from each other. Field lines do not cross or touch.
(d) 	**Two negative charges** Each field line points towards one of the negative charges. Field lines bend away from each other. Field lines do not cross or touch.
(e) 	**One positive and one negative charge** Field lines point away from the positive charge and towards the negative charge Field lines bend towards each other Field lines are continuous between the opposite charges, representing the combined effect of each charge's field

Direction of the electric force on a charged particle within an electric field

- Like charges repel and opposite charges attract.
- A **positively charged particle** will experience a force in the **same direction** as the field lines (away from positive charges and towards negative charges).
- A **negatively charged particle** will experience a force in the **opposite direction** to the field lines (towards positive charges and away from negative charges).

USEFUL TIP

When finding the direction of the force on an object within a field, the object's own field lines should be ignored.

Particles with an electric charge

The most common examples of particles with an electric charge is the electron with a negative electric charge and the proton with a positive electric charge. They both have a charge with magnitude $e = 1.6 \times 10^{-19}$ C.

Monopoles and dipoles

An isolated charge, such as those shown in Table 1(a) or (b), is a monopole: the electric field lines have a defined start or end at these points. When equally positively and negatively charged objects are close together, so the field lines have both a start point and an endpoint, they form a dipole as shown in Table 1(e).

Calculating electric field strength around a point charge

In VCE Physics we can be asked to find the field strength around a single point charge, which is a charge located entirely at a single point. The electric field strength around a point charge is non-uniform, similar to the gravitational field strength around a planet as discussed in lesson 5A.

$$E = \frac{kq}{r^2}$$

E = electric field strength around a point charge (N C^{-1} or V m^{-1}),
k = Coulomb's constant (8.99×10^9 N m^2 C^{-2}), q = electric charge generating the field (C),
r = distance from the centre of the charge (m)

Like gravitational field strength $\left(g = G\frac{M}{r^2}\right)$, electric field strength follows the inverse square law.

The strength of an electric field produced by an object is determined by the charge rather than the mass of that object.

Calculating electric force acting on a point charge

The electric force on a charged particle is given by multiplying the charge of the particle with the strength of the field at that point.

$$F = qE$$

F = electric force (N), q = electric charge experiencing the force (C),
E = electric field strength (N C^{-1} or V m^{-1})

Note that q, in this equation, is the charge **experiencing the force**, rather than the charge generating the field. This equation is equivalent to $F_g = mg$ in the context of gravitational fields.

Combining the formula for electric field strength $\left(E = \frac{kq}{r^2}\right)$ with the formula for the electric force acting on a charge ($F = qE$) we can establish Coulomb's law to calculate the electric force acting on two point charges:

$$F = \frac{kq_1 q_2}{r^2}$$

F = electric force (N), k = Coulomb's constant (8.99×10^9 N m^2 C^{-2}), q_1 = electric charge of one object (C), q_2 = electric charge of other object (C), r = distance between the centres of the charges (m)

- The magnitude of the force on each charge is equal, which is consistent with Newton's third law.
- The designation of a charge as q_1 or q_2 does not affect the result.
- From this equation we can see that if an object within an electric field has no charge, the field will not exert a force on it.

1 Worked example

Particle *X* has a charge of -4.0×10^{-8} C and particle *Y* has a charge of 5.0×10^{-8} C. The particles are separated by a distance of 2.0 metres. Take *k* to be equal to 8.99×10^{9} N m^2 C^{-2}.

a **Calculate the electric field strength due to particle *X* at a distance of 2.0 metres.**

b **Calculate the magnitude and determine the direction of the electric force acting on each particle.**

a $E = \frac{kq}{r^2}$

Use $q_X = 4.0 \times 10^{-8}$ C since we are finding the field strength **due to particle *X***. We use the magnitude of the charge to calculate field strength.

$E = \frac{8.99 \times 10^9 \times 4.0 \times 10^{-8}}{2.0^2}$

$E = 90$ N C^{-1}

b The magnitude of the electric force on each particle is equal.

$F = \frac{kq_1q_2}{r^2}$

$F = \frac{8.99 \times 10^9 \times 4.0 \times 10^{-8} \times 5.0 \times 10^{-8}}{2.0^2} = 4.5 \times 10^{-6}$ N

Alternatively we can calculate the force acting on particle *Y* due to the electric field from particle *X*.

$F = qE$

Use $q_Y = 5.0 \times 10^{-8}$ C. E is the field strength due to particle *X*.

$F = 5.0 \times 10^{-8} \times 89.9 = 4.5 \times 10^{-6}$ N

The forces are attractive, meaning the force on each particle is towards the other particle, because the charges have opposite signs.

Electric fields between charged plates 3.1.2.1.5 & 3.1.6.2 & 3.1.14.1

OVERVIEW

Charged objects experience a constant electrical force at all locations within a uniform electric field. These fields are often produced by oppositely charged parallel plates. The voltage difference across the plates and the distance between them will determine the electric field strength.

THEORY DETAILS

In a uniform electric field, all points in space have the same electric field strength and direction. Just as we learned in lesson 5A, this is shown by field lines being equally spaced and parallel to each other. A uniform electric field is found between two electrically charged plates (see Figure 1).

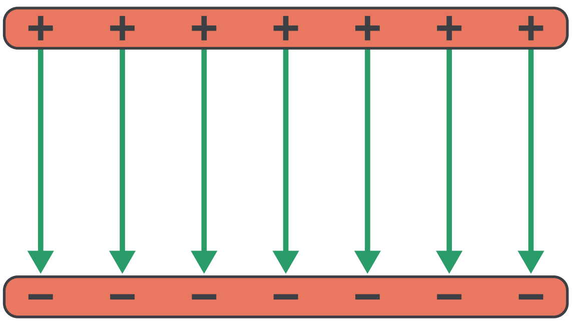


Figure 1 The electric field between the two plates is shown to be uniform by equally spaced parallel lines.

Strength of a uniform electric field

The strength of a uniform electric field is determined by the voltage difference and the distance between the charged plates.

$$E = \frac{V}{d}$$

E = electric field strength of a uniform electric field (N C^{-1} or V m^{-1}), V = voltage difference (V), d = distance between plates (m)

- As the field is uniform, the field strength is the same for all locations between the plates.
- Voltage difference may also be referred to as 'accelerating voltage' or 'potential difference'.

Work done on a charged object in a uniform electric field

The force on a charged object is given by the relationship $F = qE$. As electric field strength, E, is constant in a uniform electric field, so too is the force on a charged object. The force on a charged object in a uniform electric field is $F = \frac{qV}{d}$.

From lesson 3B, we know that $W = Fs$ when the force is constant. In the case of a charge in a uniform electric field, this formula gives the following relationships.

$$W = qEd = qV$$

W = work done (J), q = electric charge (C), E = uniform electric field strength (N C^{-1} or V m^{-1}), d = distance travelled within the uniform field (m), V = voltage difference (V)

We also know that work is associated with a transformation of energy. In the case of a charged object being accelerated through an electric field, it will lose electric potential energy and gain kinetic energy if the charge moves in the direction of the force. This gives the following relationship.

$$\frac{1}{2}mv^2 = qV$$

m = mass of object (kg), v = speed of object (m s^{-1}), q = electric charge (C), V = voltage difference (V)

Linear particle accelerators

Scientists use electric fields between two plates to accelerate particles like electrons and protons up to very high speeds. This may also be referred to as an electron gun.

Figure 2 shows a simplified version of a particle accelerator. A power source creates a voltage difference across two plates. Once an electron (negative charge) enters the electric field, it experiences a force to the right: it is repelled by the negatively charged plate on the left and attracted to the positively charged plate on the right. This force accelerates the electron.

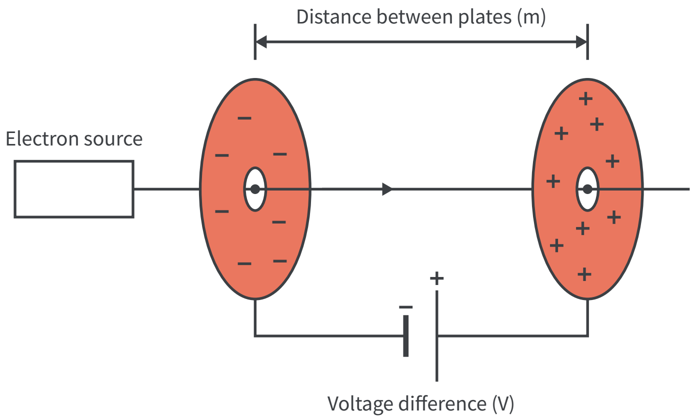
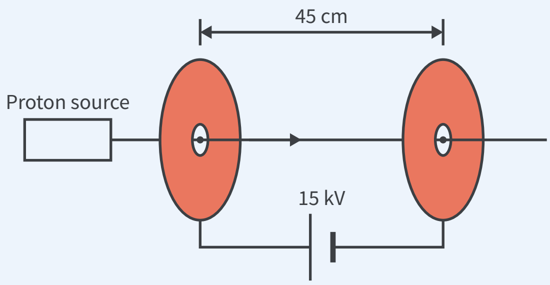


Figure 2 A particle accelerator for electrons

2 Worked example

The uniform electric field generated by two electrically charged plates accelerates an initially stationary proton over a distance of 45 cm.

Mass of proton	1.7×10^{-27} kg
Charge of proton	$+1.6 \times 10^{-19}$ C
Accelerating voltage	15 kV
Distance between plates	45 cm



a **Calculate the electric field strength between the two plates.**

b **Calculate the speed of the proton when it exits the electric field. Ignore relativistic effects.**

a $E = \frac{V}{d}$

$E = \frac{15 \times 10^3}{0.45}$

$E = 3.3 \times 10^4\ \text{V m}^{-1}$

b $\frac{1}{2}mv^2 = qV$

$\frac{1}{2} \times 1.7 \times 10^{-27} \times v^2 = 1.6 \times 10^{-19} \times 15 \times 10^3$

$v = 1.7 \times 10^6\ \text{m s}^{-1}$

In questions such as this one, be careful not to confuse v with V. It is also important to check that your final answer is realistic (v should never be greater than c, the speed of light in a vacuum).

Theory summary

- In electric field diagrams
  - field lines point away from positive charges and towards negative charges.
  - field lines show the direction of the electric force that a positive charge would experience at each point in space.
- Electric field strength around a point charge follows the inverse square law.
- Opposite charges attract and like charges repel.

Table 2 Summary of formulas for electric fields

Uniform fields	All fields	Non-uniform fields around point charges
$E = \frac{V}{d}$	$F = qE$	$E = \frac{kq}{r^2}$
$W = qEd = qV$		$F = \frac{kq_1q_2}{r^2}$
$\frac{1}{2}mv^2 = qV$		

KEEN TO INVESTIGATE?

PhET 'Charges and fields' simulation
https://phet.colorado.edu/en/simulation/charges-and-fields

YouTube video: CrashCourse – Electric Charge: Crash Course Physics #25
https://youtu.be/TFlVWf8JX4A

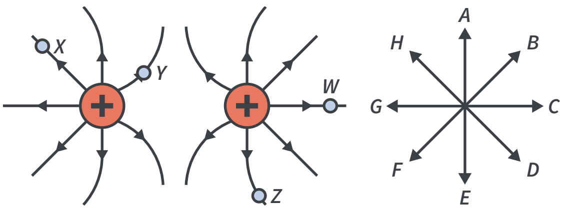
YouTube video: CrashCourse – Electric Fields: Crash Course Physics #26
https://youtu.be/mdulzEfQXDE

6A Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–4.

Two point charges and their associated electric field are shown.



Question 1

What is the direction of the electric field at point *X* (*A-H*)?

Question 2

What is the direction of the field at point *Y* (*A-H*)?

Question 3

If a **positively** charged particle was placed at point *Z*, in which direction would it accelerate (*A-H*)?

Question 4

If a **negatively** charged particle was placed at point *W*, in which direction would it accelerate (*A-H*)?

Question 5

Which of the following sets of equations applies to non-uniform electric fields?

A $E = \frac{kq}{r^2}, F = \frac{kq_1q_2}{r^2}, F = qE$

B $E = \frac{kq}{r^2}, F = \frac{kq_1q_2}{r^2}, W = qEd$

C $E = \frac{V}{d}, W = qV, \frac{1}{2}mv^2 = qV, F = qE$

D $E = \frac{V}{d}, W = qV, \frac{1}{2}mv^2 = qV, F = \frac{kq_1q_2}{r^2}$

Question 6

Which of the following set of equations applies to uniform electric fields?

A $E = \frac{kq}{r^2}, F = \frac{kq_1q_2}{r^2}, F = qE$

B $E = \frac{kq}{r^2}, F = \frac{kq_1q_2}{r^2}, W = qV$

C $E = \frac{V}{d}, W = qV, \frac{1}{2}mv^2 = qV, F = qE$

D $E = \frac{V}{d}, W = qV, \frac{1}{2}mv^2 = qV, F = \frac{kq_1q_2}{r^2}$

EXAM-STYLE QUESTIONS

This lesson

Question 7 (1 MARK)

Students are considering how to make an electric dipole. Which of the following is a valid method?

A Bringing two electrons close together.

B Isolating a single proton.

C Bringing a proton and an electron close together.

D It is not possible to create an electric dipole.

Question 8 (1 MARK)

Three charges are arranged in a line as shown.

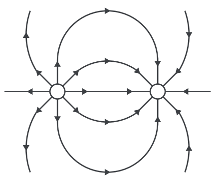
Copy the diagram, and draw an arrow at point *G* to show the direction of the electric field at that point.

Adapted from 2017 VCAA Exam Section B Q1

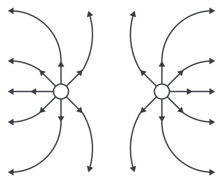
Question 9 (1 MARK)

Which of the following shows the electric field pattern surrounding two equal magnitude negative charges?

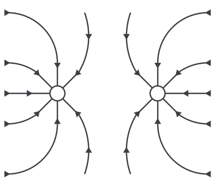
A



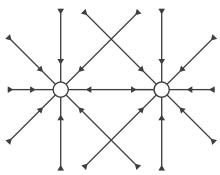
B



C



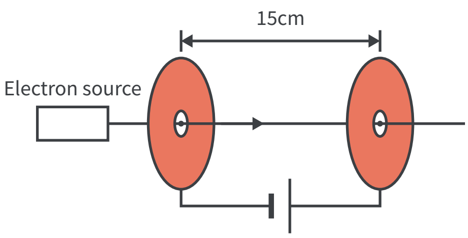
D



Question 10 (3 MARKS)

An electric field between two charged plates is being used to accelerate electrons from rest.

Mass of electron	9.1×10^{-31} kg
Charge of electron	-1.6×10^{-19} C
Electric field strength	6.0×10^{5} V m^{-1}
Distance between plates	15 cm



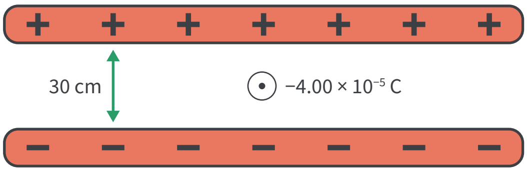
a Show that the magnitude of the accelerating voltage between the plates is 90 kV. (1 MARK)

b Calculate the speed of the electron as it exits the electric field. Ignore relativistic effects. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q1

Question 11 (4 MARKS)

An experiment is set up to calculate the mass of a charged sphere. In this experiment, an electrical force is used to balance out the gravitational force on the sphere. Two electrically charged plates are placed 30 cm vertically apart with a voltage difference of 1.67×10^3 V between them. The sphere has a charge of -4.00×10^{-5} C. The charged sphere is placed between the two plates and remains stationary.



a Calculate the electric field strength needed to keep the charged sphere stationary between the two plates. (2 MARKS)

b Hence find the mass of the sphere. (2 MARKS)

Adapted from 2017 VCAA Exam Section A Q2

Question 12 (2 MARKS)

In a particle accelerator, electrons are accelerated from rest by a uniform field of 2.0×10^3 V m^{-1} up to a speed of 6.3×10^6 m s^{-1}. Take the charge of an electron to be -1.6×10^{-19} C and its mass to be 9.1×10^{-31} kg.

What is the distance, in centimetres, over which the electrons are accelerated? Ignore relativistic effects.

Adapted from 2016 VCAA Exam Section A Q2

Question 13 (5 MARKS)

A metal sphere has a charge of $+3.4 \times 10^{-8}$ C. A larger sphere with a charge of -5.4×10^{-9} C is placed 3.0 mm to the right of the first sphere.

In calculations, treat both spheres as point charges and $k = 8.99 \times 10^9$ N m^2 C^{-2}.

a What is the direction of the electric field due to the smaller sphere at the point where the larger sphere is located? (1 MARK)

b What is the **magnitude** and **direction** of the force on the larger sphere? (2 MARKS)

c Use your answer from part **b** to determine the **magnitude** and **direction** of the force on the larger sphere if it were moved three times further away (2 MARKS)

Previous lessons

Question 14 (3 MARKS)

A 2.5 kg ball is thrown with an initial velocity of 22 m s^{-1} upwards. Assume there is no air resistance.

a What is the initial kinetic energy of the ball? (1 MARK)

b Use your answer from part **a** to determine the maximum height that the ball reaches above its initial position (2 MARKS)

Question 15 (2 MARKS)

A satellite is in orbit around Earth and experiences a force of 230 N. The satellite is orbiting at a distance of 9.00×10^6 m from the centre of the Earth, the mass of Earth is 5.98×10^{24} kg, and $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Calculate the mass of the satellite.

Key science skills

Question 16 (5 MARKS)

Students set up an experiment to measure the force on a particular charged sphere at different distances from a charged plate. They recorded their data in a table.

Distance (cm)	Electric force on charged sphere (N)
15	12.1
30	12.3
45	12.1
60	11.8

a Graph the electric force versus distance. Label each axis, including units, and draw a line of best fit through the data. (3 MARKS)

b Hence determine whether the electric field created by the charged plate is uniform or non-uniform in the region measured. Justify your answer. (2 MARKS)

6B MAGNETIC FIELDS

This lesson will introduce magnetic fields, how they are created, and the pattern of magnetic fields around bar magnets, current-carrying wires, and coils. The presence of magnetic fields around current-carrying wires demonstrates a relationship between electricity and magnetism.

6A Electric fields	6B Magnetic fields	6C Magnetic forces on charged particles	6D DC motors

Study design key knowledge dot points

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and apply theoretically and practically a vector field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- identify fields as static or changing, and as uniform or non-uniform
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other

Key knowledge units

Magnetic fields	3.1.2.1.2 & 3.1.5.2
Magnetic field patterns	3.1.2.1.3 & 3.1.4.1

No previous or new formulas for this lesson

Definitions for this lesson

bar magnet a permanent magnet in the shape of a prism

electromagnet a magnet created by an electric current

magnetic field a vector field that arises from the movement of charge

permanent magnet an object with material properties that cause it to produce a magnetic field

solenoid an electromagnet made from coils of wire

static field a field that is not changing over time

Magnetic fields 3.1.2.1.2 & 3.1.5.2

OVERVIEW

A magnetic field is a vector field that arises from the movement of charge. These fields can be static or changing. Similar to electric and gravitational fields, we represent magnetic fields using field diagrams.

THEORY DETAILS

We have all used magnets and seen how they can exert a force at a distance. Magnets create a vector force field around them which is caused by the movement of charge. In a permanent magnet, the constant movement of electrons within the material aligns so that their individual magnetic fields add up to create an overall stronger magnetic field. In an electromagnet, an electric current creates a magnetic field.

All magnetic fields form a closed loop. That is, the field does not originate from or finish at any magnetic 'source'. For this reason, a magnetic monopole has not been discovered (...yet).

Static fields and changing fields

A static field is a field that is not changing over time, while a changing field does change over time. For magnetic fields:

- A permanent magnet has a
  - static field if the magnet itself is stationary.
  - changing field if the magnet is in motion.
- An electromagnet has a
  - static field if the current is constant and the electromagnet is stationary.
  - changing field if the current is changing or the electromagnet is in motion.

Conventions for representing vectors

When drawing vectors, including field lines, in three dimensions (which is required in the case of magnetic fields), specific conventions must be followed. Since a page has only two dimensions, we define the extra directions of 'into the page' and 'out of the page' to form our third dimension. Figure 1 is an example of the use of the 'into the page' convention in VCE Physics exam questions.

Table 1 Drawing conventions for vectors and field lines into and out of the page.

Vector/field direction	Drawing convention
Into the page	×
Out of the page	●

USEFUL TIP

A memory tool for distinguishing between vectors that are going into and out of a page is to visualise the vector as an arrow. If we shot an arrow into a page we would see the crossed feathers at the back of the arrow. An arrow shot out of the page would show its circular tip first, hence we would see a circle.

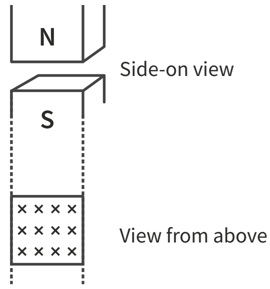


Figure 1 A magnetic field represented as being 'into the page' in the 2018 VCAA Exam Section B Q2a.

Magnetic field patterns 3.1.2.1.3 & 3.1.4.1

OVERVIEW

Magnetic field patterns are represented by field lines which flow in loops from the north to the south magnetic poles. Field patterns represent both the direction and magnitude of a field at each point in space.

THEORY DETAILS

Magnetic field patterns around bar magnets

The magnetic field pattern around a bar magnet is a series of loops which

- flow from the north pole (N) to the south pole (S) outside the magnet.
- are closer together where the field is stronger.
- never touch or cross.

Note that the north and south poles simply represent the ends of the magnet where the field lines exit and enter. The field lines form complete loops when they flow back through the magnet itself, however we do not draw these internal lines in VCE Physics. This is why there is no known way to separate north poles from south poles in order to create monopoles.

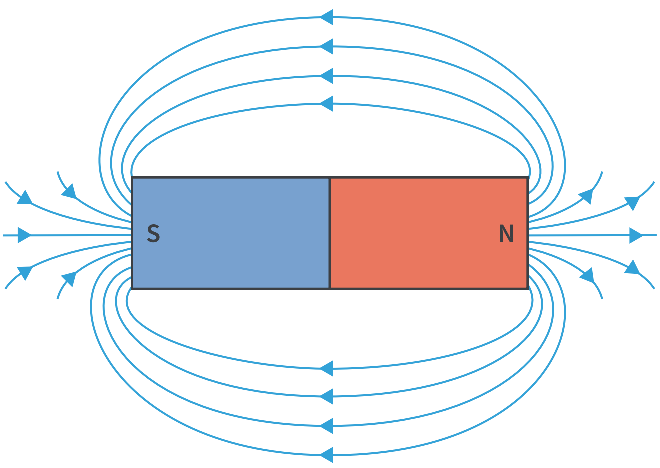


Figure 2 The magnetic field around a bar magnet.

The Earth is essentially a very large bar magnet with magnetic poles that are the **opposite** of their geographic names. On the surface of the Earth near the equator, the field lines flow parallel to the surface from the geographic South Pole, which is a magnetic north pole, to the geographic North Pole, with is a magnetic south pole. Hence, a magnetic compass will point its north needle towards the Earth's geographic North Pole.

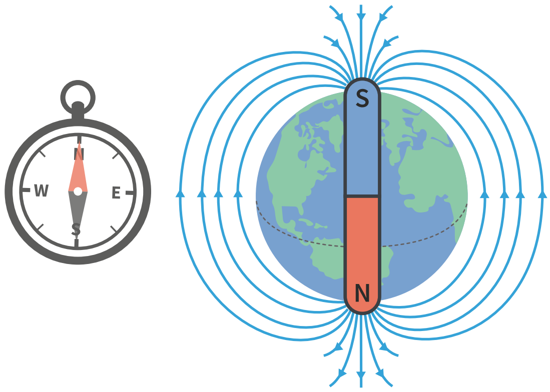


Figure 3 The Earth's magnetic field. A compass will orient its north needle towards Earth's **geographic** North Pole as shown.

The magnetic field pattern around multiple bar magnets with opposite (unlike) poles facing each other introduces field lines that flow from the north pole of one magnet to the south pole of the other. The field in the small region between opposite poles can be approximated as uniform, with the field lines between the poles drawn parallel. This is shown in Figure 4.

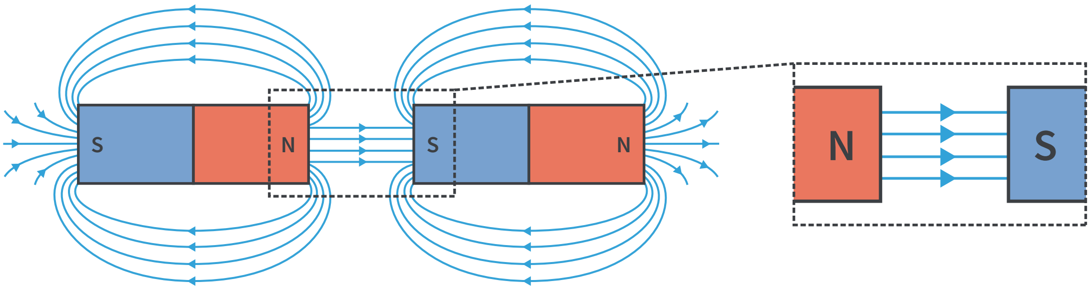


Figure 4 The magnetic field in a small region between bar magnets with opposite poles facing each other.

The magnetic field pattern around multiple bar magnets with like poles facing each other introduces field lines that diverge between the like poles. The direction of the field lines is still from north to south. This is shown in Figure 5 and 6.

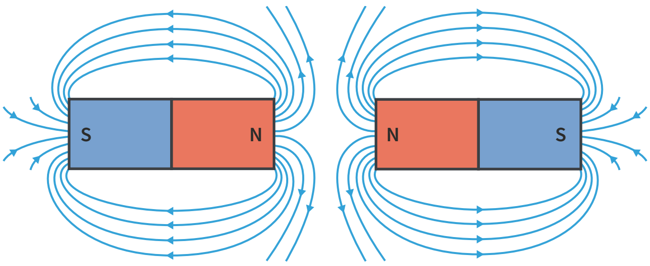


Figure 5 The magnetic field between bar magnets with north poles facing each other.

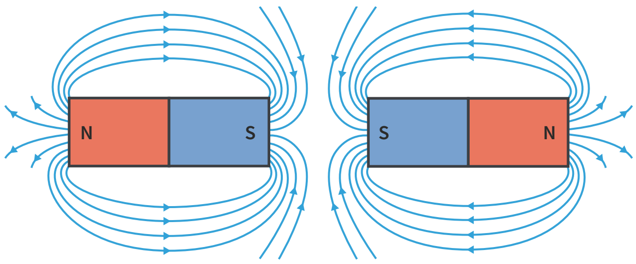


Figure 6 The magnetic field between bar magnets with south poles facing each other.

Magnetic field patterns around straight current-carrying wires

A current-carrying wire creates a circular magnetic field around it. The direction of the circular field is determined by using the **right-hand grip** rule. For this rule, the thumb indicates the direction of current and the curled grip indicates the direction of the field lines.

The strength of a magnetic field around a current-carrying wire is proportional to the magnitude of current flowing in the wire, and decreases radially outward from the wire.

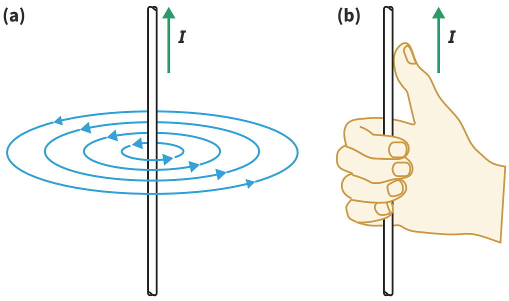


Figure 7 **(a)** The magnetic field around a current-carrying wire. For clarity, the field is not shown along the whole length of the wire. **(b)** Determining the direction of field lines using the right-hand grip rule.

Magnetic field patterns around loops

A current-carrying loop also creates a magnetic field. For a square loop, analysing the field around each edge like in Figure 8(a) helps us to find the total field of the loop, which is shown (in the plane of the page) in Figure 8(b). A circular current-carrying loop creates a similar magnetic field, as shown in Figure 8(c).

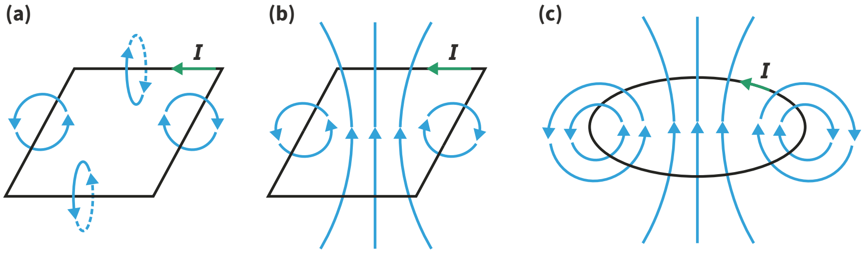


Figure 8 **(a)** The circular magnetic field around each side of a current-carrying square loop add up (using vector addition) to create **(b)** a stronger resultant magnetic field in a single direction through the middle of the loop. The total field of the loop is only shown in one plane. **(c)** The resultant magnetic field around a current-carrying circular loop shown in one plane.

To determine the direction of the magnetic field **through the middle** of a current-carrying loop, use the **right-hand coil rule**. The curled fingers represent the current direction and the thumb represents the direction of the magnetic field. This rule is also known as the right-hand solenoid rule or the right-hand loop rule.

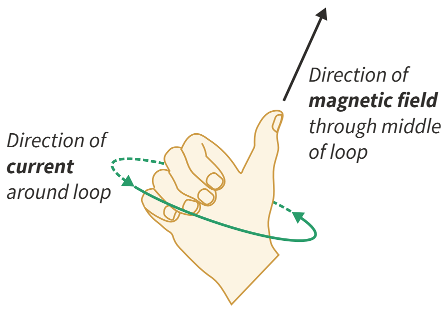


Figure 9 The right-hand coil rule, with fingers representing current direction, determines the direction of the magnetic field through the middle of a current-carrying loop.

Magnetic field patterns around solenoids

A current-carrying coil of wire is called a solenoid, which is a type of electromagnet. The magnetic field of a solenoid is the sum of the fields created by each loop within the coil. This results in a strong field along the solenoid's length axis, and a weaker magnetic field outside the radius of the solenoid.

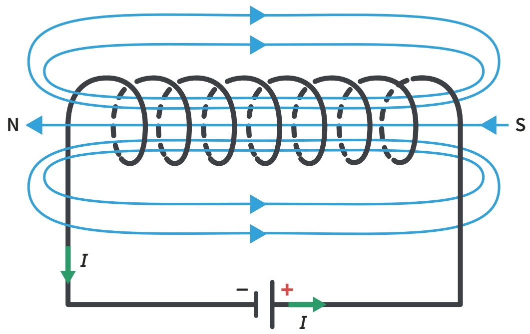


Figure 10 The magnetic field created by a solenoid, showing distinct north and south poles. Note that the field is strongest along the length axis of the solenoid, and is weaker outside the radius of the solenoid.

To determine the direction of the magnetic field created by the solenoid (inside the solenoid), use the right-hand coil rule. The curled fingers represent the current direction in each loop, which is dependent on both **the way the loops are coiled** as well as **the orientation of the current source**. When the current source is a cell, like in Figure 10, the current flows from the long line (+) to the short line (-).

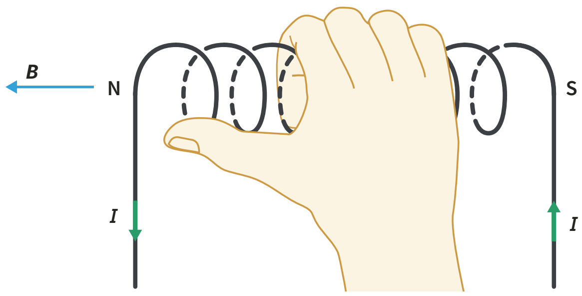


Figure 11 The right-hand coil rule with fingers representing current direction determines the direction of the magnetic field created by a solenoid (when measured inside the solenoid).

Theory summary

- Magnetic fields are created by permanent magnets or electromagnets as a result of the movement of charge.
- There is no known magnetic monopole.
- Magnetic fields can be static or changing.
- The field around a bar magnet flows from north to south.
- Current-carrying wires create circular fields around them, with direction found by the right-hand grip rule.
- The direction of a field created by a current-carrying loop is found using the right-hand coil rule.
- A solenoid creates a magnetic field that is strong along its length axis.
- The direction of a field created inside a solenoid is found using the right-hand coil rule.
  - The direction of the current around the solenoid determines the direction of the field, which means that the way that a solenoid is coiled and the orientation of the current source must be considered when determining field direction.

KEEN TO INVESTIGATE?

Falstad '3D Magnetic field' simulation
https://www.falstad.com/vector3dm/fullscreen.html

Youtube video: MinutePhysics - MAGNETS: How Do They Work?
https://youtu.be/hFAOXdXZ5TM

Youtube video: Veritasium - How Special Relativity Makes Magnets Work
https://youtu.be/1TKSfAkWWN0

6B Questions

THEORY REVIEW QUESTIONS

Question 1

A static magnetic field is a field that

A is changing over time.

B is not changing over time.

C is created by a static charge.

D is increasing over time.

Question 2

Which of the following statements is false?

A There are no known magnetic monopoles.

B A constant current in a wire will create a magnetic field.

C Magnetic fields flow outward from magnetic monopoles.

D Field lines for a bar magnet always point from north to south.

Question 3

Which rule is used to determine the magnetic field direction around a straight current-carrying wire?

A Right-hand coil rule

B Right-hand grip rule

C Right-hand palm rule

D Right-hand slap rule

Question 4

Which rule is used to determine the magnetic field direction through the middle of a current-carrying loop?

A Right-hand coil rule

B Right-hand grip rule

C Right-hand palm rule

D Right-hand slap rule

Question 5

The magnetic field between opposite poles of two stationary bar magnets is approximated as

A a static, non-uniform field.

B a changing, non-uniform field.

C a static, uniform field.

D a changing, uniform field.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (9 MARKS)

Four magnetic fields are being analysed.

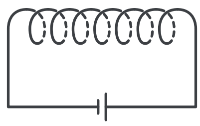
a **i** Draw the magnetic field in the space between these two bar magnets. Use four field lines. (1 MARK)

ii Is the magnetic field between these magnets uniform or non-uniform? (1 MARK)

b **i** Draw the magnetic field in the space between these two bar magnets. Use four field lines. (1 MARK)

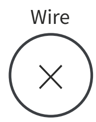
ii Is the magnetic field between these magnets uniform or non-uniform? (1 MARK)

c **i** Draw the magnetic field through and around this solenoid. Use five field lines. (2 MARKS)



ii State whether the field is uniform or non-uniform inside the solenoid. (1 MARK)

d **i** Draw the magnetic field around this current-carrying wire. Use four field lines. (1 MARK)

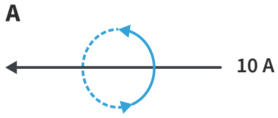


ii State whether the field is uniform or non-uniform. (1 MARK)

Question 7 (1 MARK)

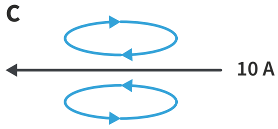
A wire carries a 10 A current to the left. Which of the following diagrams best shows the magnetic field produced by the current?

A

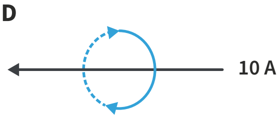


B

C



D



Adapted from 2018 VCAA Exam Section A Q3

Question 8 (1 MARKS)

Einstein's granddaughter is experimenting with magnets. To create a magnetic monopole, she should

A run a strong current through a square coil.

B snap a bar magnet in half between the north and south poles.

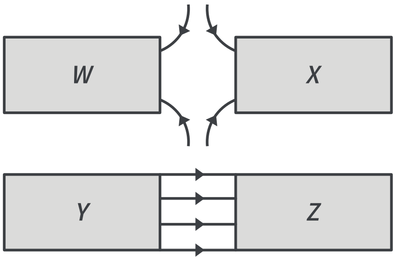
C cut a solenoid in half between the north and south poles.

D There is no known way to create a magnetic monopole.

Adapted from 2017 VCAA Exam Section A Q1

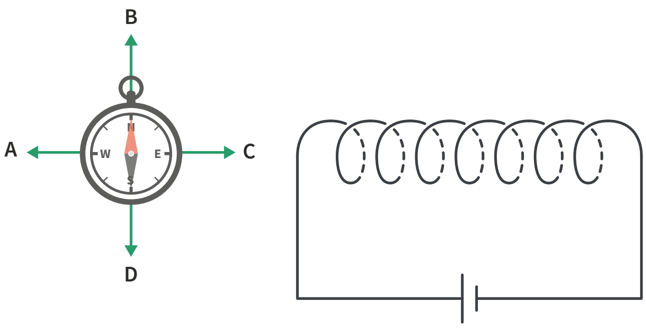
Question 9 (2 MARKS)

A student has drawn field lines between the poles of two bar magnets in two different orientations. Determine the pole type (north or south) of poles *W, X, Y* and *Z*.



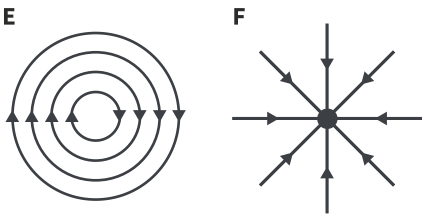
Question 10 (1 MARK)

Current is made to run through a solenoid from a battery. A small compass, which orients itself so that its north pole points in the direction of field lines around it, is next to the solenoid. Determine the direction (A, B, C, or D) that the north pole of the compass would point when the solenoid is turned on.



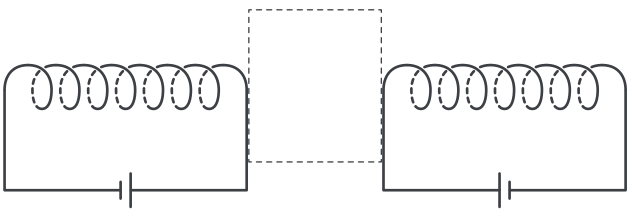
Question 11 (3 MARKS)

Which of these fields (E or F) could be magnetic fields? If a field cannot be magnetic, explain why.



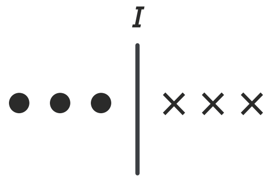
Question 12 (2 MARKS)

Two solenoids are brought close together. In the dashed area, use four field lines to show the shape of the magnetic field between the solenoids.



Question 13 (1 MARK)

A current-carrying wire is creating a magnetic field. Determine the direction of the current *I*.



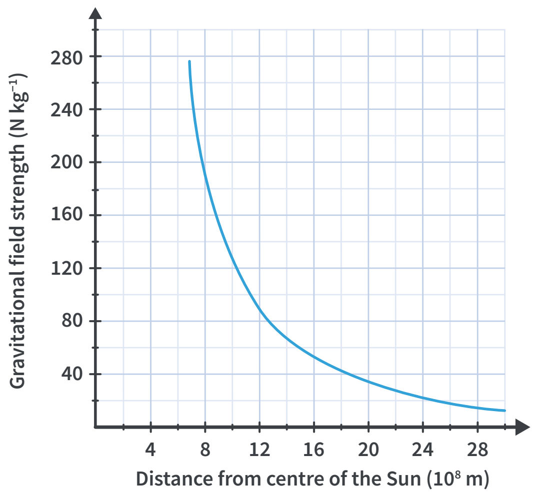
Previous lessons

Question 14 (2 MARKS)

A ball of mass 2.00 kg falls from a height of 1000 m. By the time it reaches the ground, what will its speed be? Assume that its initial speed is zero and that there is no air resistance.

Question 15 (3 MARKS)

Using the graph, estimate the change in gravitational potential energy of a 200 kg asteroid when moving from 14×10^8 m to 26×10^8 m from the centre of the Sun.



Key science skills

Question 16 (1 MARK)

Students are measuring the direction of a magnetic field with the compass shown. They record the bearing which the magnet's north pole points to. Determine the uncertainty in this measuring device.

Image: Pikepicture/Shutterstock.com

6C MAGNETIC FORCES ON CHARGED PARTICLES

This lesson will investigate the forces on charged particles and current-carrying wires caused by magnetic fields. We will learn the conditions required for a force to be present, the magnitude of magnetic forces, and how to determine the direction of magnetic forces. The interaction between charges and magnetic fields is further evidence that electric fields and magnetic fields are two versions of the same thing, known as ‘electromagnetism’.

6A Electric fields	6B Magnetic fields	6C Magnetic forces on charged particles	6D DC motors

Study design key knowledge dot points

- analyse the use of a magnetic field to change the path of a charged particle, including:
  - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel
  - the radius of the path followed by a low-velocity electron in a magnetic field: $qvB = \frac{mv^2}{r}$
- investigate and analyse theoretically and practically the force on a current carrying conductor due to an external magnetic field, $F = nILB$, where the directions of I and B are either perpendicular or parallel to each other
- model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field)

Key knowledge units

Magnetic forces on charged particles	3.1.7.1
Circular motion in magnetic fields	3.1.7.2
Magnetic forces on current-carrying wires	3.1.12.1

Formulas for this lesson

Previous lessons		New formulas
2D	* $a = \frac{v^2}{r}$	* $F = qvB$
		* $r = \frac{mv}{qB}$
		* $F = nILB$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

conventional current current that is assumed to consist of flowing positive charges so that the direction of current is the direction a positive charge would move

Magnetic forces on charged particles 3.1.7.1

OVERVIEW

A charged particle will experience a magnetic force when it is moving through a magnetic field at an angle to its field lines. The direction of the force is determined by using the right-hand palm rule.

THEORY DETAILS

The conditions for a magnetic force on a charged particle

When moving through a magnetic field, a charged particle will experience a force which depends on the angle between its direction of motion and the magnetic field lines. In VCE Physics we only consider motion of charged particles that is perpendicular or parallel to the magnetic field.

- The magnetic force is a maximum when the direction of motion is perpendicular (at a right angle) to the magnetic field lines.
- There is no magnetic force when the direction of motion is parallel to the magnetic field lines or if the particle is stationary.

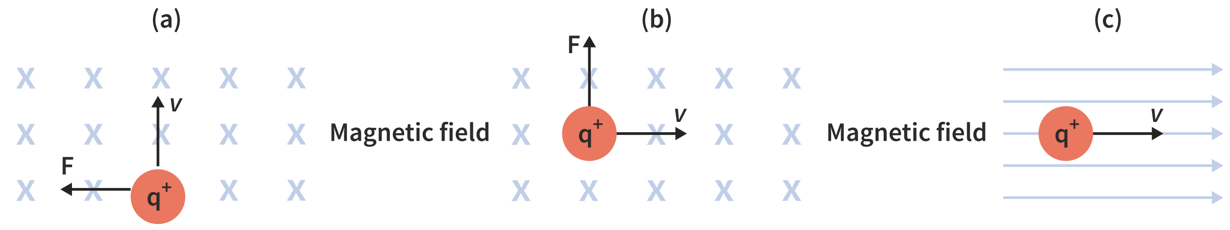


Figure 1 **(a)**, **(b)** A charged particle will experience a force when moving perpendicular to a magnetic field. **(c)** A charged particle will not experience a force when moving parallel to a magnetic field.

Direction of force on a charged particle moving perpendicular to a magnetic field

The direction of the magnetic force is always perpendicular to both the direction of motion of the charged particle and the direction of the magnetic field. The direction of the magnetic force on a positively charged particle is determined by the right-hand palm rule (also known as the right-hand slap rule).

- The thumb represents the direction of motion of the positively charged particle (or current flow).
- The fingers represent the direction of the magnetic field lines.
- The palm represents the direction of the magnetic force.

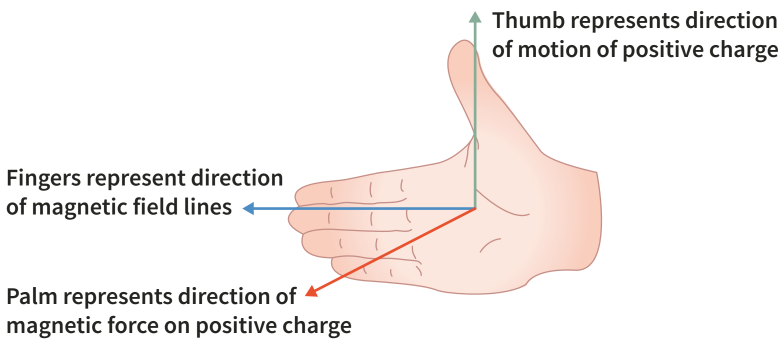


Figure 2 The direction of the magnetic force on a positively charged particle is determined by the right-hand palm rule.

To determine the direction of the magnetic force on a **negatively** charged particle, point the thumb opposite to the direction of motion of the particle, as shown in Figure 3. This means that the force on a negatively charged particle is in the **opposite direction** to the force on a positively charged particle.

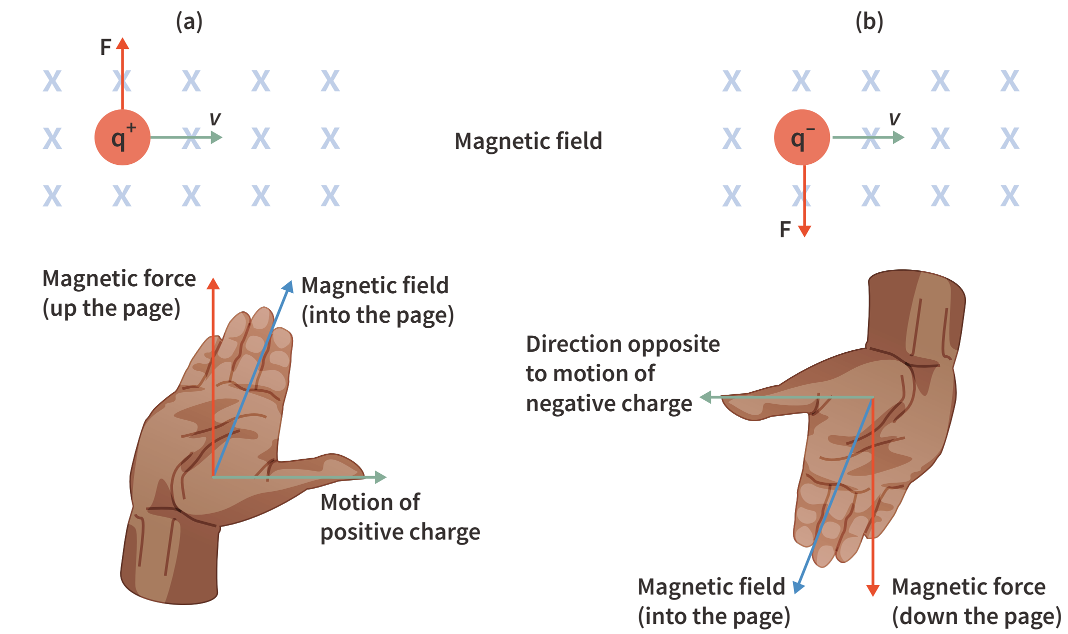


Figure 3 **(a)** Determining the direction of the magnetic force on a positively charged particle moving perpendicular to a magnetic field. **(b)** Determining the direction of the magnetic force on a negatively charged particle moving perpendicular to a magnetic field by pointing the thumb opposite to the direction of motion.

Magnitude of magnetic force on a charged particle

Equations involving magnetic fields will use the variable B to represent magnetic field strength, which is measured in tesla (T). It is common for magnetic field strength to be far smaller than 1 T. The Earth's magnetic field strength ranges from 2.5×10^{-5} T to 6.5×10^{-5} T.

The magnitude of the magnetic force on a charged particle moving **perpendicular** to a magnetic field of strength B is:

$$F = qvB$$

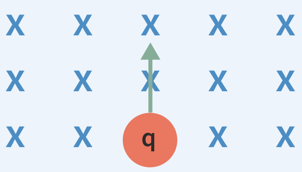
F = magnitude of magnetic force (N), q = magnitude of charge (C), v = speed of particle (m s^{-1}), B = magnetic field strength (T)

USEFUL TIP

Before completing any magnetic force calculations, check that the direction of motion of the charge is perpendicular to the magnetic field.

1 Worked example

A charged particle is moving up the page through a magnetic field of strength B = 0.50 T at 20 m s^{-1}. The magnetic field direction is into the page.



Determine the magnitude and direction of the magnetic force acting on the charged particle if it is

a a proton.

b an electron.

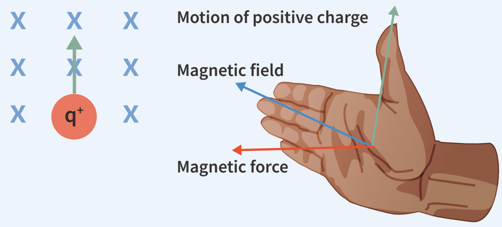
a The charge is moving perpendicular to the magnetic field so a force will be present.

The charge of a proton is $+1.6 \times 10^{-19}$ C.

$F = qvB = 1.6 \times 10^{-19} \times 20 \times 0.50$

$F = 1.6 \times 10^{-18}$ N

Use the right-hand palm rule with thumb pointing up the page in the direction of motion, and fingers pointing into the page. The palm (and force) points left.



Therefore, the magnetic force is 1.6×10^{-18} N to the left.

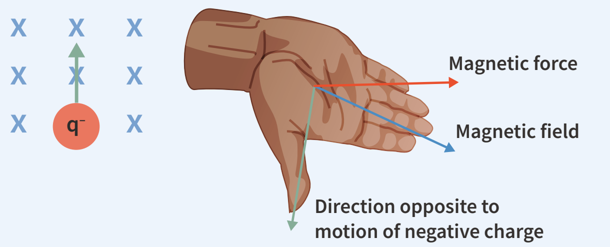
b The charge is moving perpendicular to the magnetic field so a force will be present.

The charge of an electron is -1.6×10^{-19} C, so its magnitude is 1.6×10^{-19} C.

$F = qvB = 1.6 \times 10^{-19} \times 20 \times 0.50$

$F = 1.6 \times 10^{-18}$ N

Since the particle has a negative charge, use the right-hand palm rule with the thumb pointing down the page (opposite to the direction of motion) and fingers pointing into the page. The palm (and force) points right.



Therefore, the magnetic force is 1.6×10^{-18} N to the right.

Circular motion in magnetic fields 3.1.7.2

OVERVIEW

Charged particles moving perpendicular to a magnetic field will travel in uniform circular motion. The magnetic force on a charged particle acts as the centripetal force.

THEORY DETAILS

When a charged particle is moving in a magnetic field perpendicular to its field lines, the magnetic force always acts perpendicular to the motion of the particle and remains constant in magnitude. From lesson 2D, we know that a net force with constant magnitude that is always in a perpendicular direction to an object's motion will result in uniform circular motion. Therefore, in the absence of any other forces, a charged particle moving perpendicular to a magnetic field will exhibit uniform circular motion.

Since the direction of force will be opposite for positive and negative charges, the direction of rotation will be **opposite** for positive and negative charges.

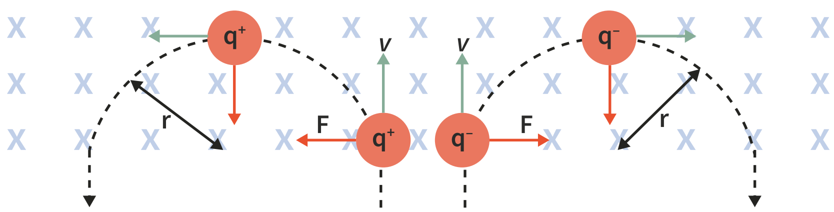


Figure 4 Charged particles moving perpendicular to a magnetic field will exhibit uniform circular motion. In otherwise identical scenarios, positively and negatively charged particles follow circular paths with opposite directions. The particles in this diagram have the same mass and charge magnitude.

Circular motion in particle accelerators

Particle accelerators are constructed with both a linear electric field component (as covered in lesson 6A) and a magnetic field component that will direct the charged particle along a circular path. The direction that the magnetic field curves the accelerated particle depends on whether the charge is negative or positive.

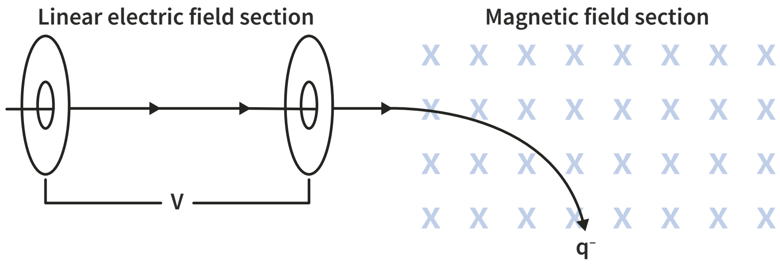


Figure 5 The electric and magnetic field sections inside a particle accelerator. In the magnetic field section, the charged particle is directed along a circular path.

Circular motion calculations

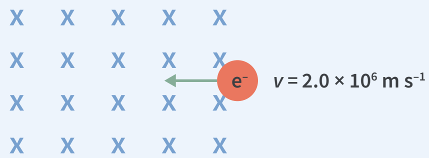
During uniform circular motion in a magnetic field, the force on a charged particle, $F = qvB$, is equal to the centripetal force $F = \frac{mv^2}{r}$. By equating these two formulas ($qvB = \frac{mv^2}{r}$) and rearranging we can find the radius of a charged particle exhibiting circular motion in a magnetic field.

$$r = \frac{mv}{qB}$$

r = radius of circular motion (m), m = mass of particle (kg), v = speed of particle (m s^{-1}), q = magnitude of charge (C), B = magnetic field strength (T)

2 Worked example

a **An electron enters a uniform magnetic field with field strength B = 2.0 × 10^{-3} T, moving in a direction perpendicular to the magnetic field and turns through one quarter of a circle. The initial speed of the electron is 2.0 × 10^{6} m s^{-1}.**

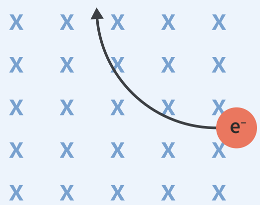


i **Draw the path of the electron through the magnetic field.**

ii **Calculate the radius of the electron's circular motion. Ignore relativistic effects.**

b **A proton moving at a speed of 7.0 × 10^{7} m s^{-1} inside a perpendicular magnetic field is undergoing circular motion with a radius of 0.30 m. Determine the strength of the surrounding magnetic field. Ignore relativistic effects, and take the mass of a proton to be 1.7 × 10^{-27} kg.**

a **i** Use the right-hand palm rule with the thumb pointing to the right (opposite to the direction of motion since the electron has a negative charge) and with fingers pointing into the page. The force is upwards which indicates the circular path is clockwise.



Make sure to draw one quarter of a circle as stated in the question.

ii The mass of an electron is 9.1 × 10^{-31} kg.

The magnitude of the charge of an electron is 1.6 × 10^{-19} C.

$$r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 2.0 \times 10^{6}}{1.6 \times 10^{-19} \times 2.0 \times 10^{-3}}$$

$r = 0.00569 = 5.7 \times 10^{-3}$ m

b $r = \frac{mv}{qB}$ $\therefore 0.30 = \frac{1.7 \times 10^{-27} \times 7.0 \times 10^{7}}{1.6 \times 10^{-19} \times B}$

$B = 2.5$ T

Magnetic forces on current-carrying wires 3.1.12.1

OVERVIEW

Current-carrying wires experience magnetic forces when the current is at an angle to an external magnetic field. The magnitude of the force is dependent on this angle, the current, the number of wires, the length of the wires within a magnetic field, and the magnetic field strength. The direction of the force is determined using the right-hand palm rule.

THEORY DETAILS

Electric current is equivalent to the movement of multiple charged particles in the same direction. Since a charged particle moving at an angle to a magnetic field experiences a magnetic force, the moving charged particles inside a current-carrying wire also experience a magnetic force. Because the charged particles must remain inside the wire, we can say that there is a magnetic force on the current-carrying wire.

- Current direction is defined as the direction of the flow of positive charge. This flow is called conventional current, and in an electric circuit conventional current flows from the positive terminal to the negative terminal of a power source.
- This means that we can use the right-hand palm rule with the **thumb representing conventional current direction** to determine the direction of the magnetic force on a current-carrying wire.

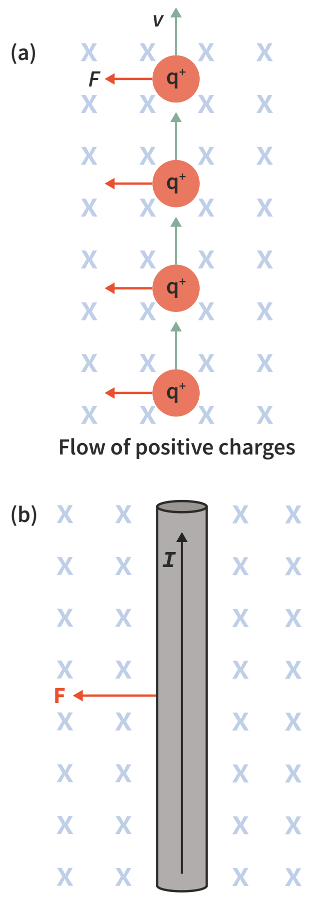


Figure 6 **(a)** The magnetic forces on a flow of positive charges. **(b)** The magnetic force on a current-carrying wire.

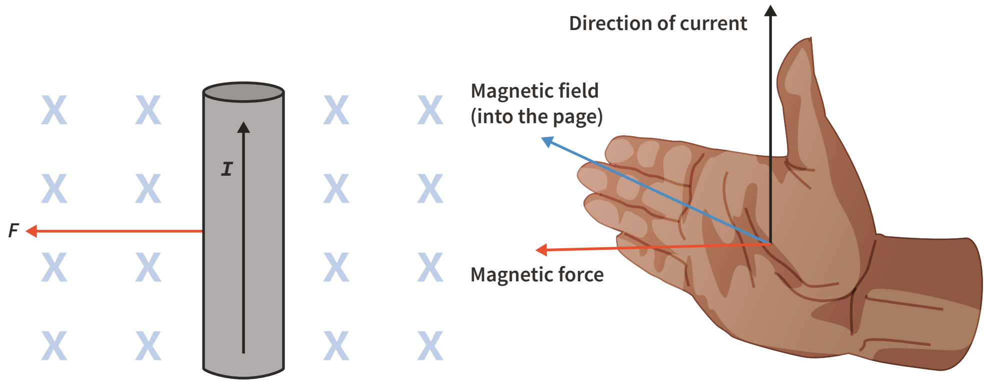


Figure 7 Using the right-hand palm rule to determine the force on a current-carrying wire.

Magnitude of magnetic force on a current-carrying wire

In VCE Physics we consider only current that is flowing perpendicular or parallel to a magnetic field. If the current is parallel to the magnetic field, there is no magnetic force.

The magnitude of the magnetic force on a current-carrying wire that is **perpendicular** to a magnetic field is:

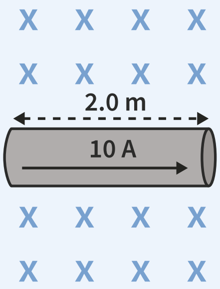
$$F = nILB$$

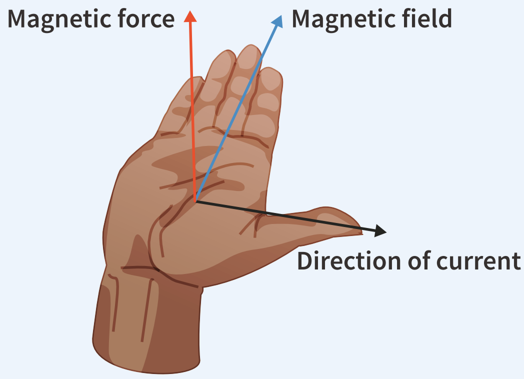
F = magnitude of magnetic force (N), n = number of wires (no units), I = current perpendicular to magnetic field (A), L = length of wire within magnetic field (m), B = magnetic field strength (T)

Note that we always describe this force as the force on 'a current-carrying wire' as opposed to the force on 'a wire', since the force specifically acts on the moving charge.

3 **Worked example**

A bundle of 10 wires carrying 10 A each pass through a perpendicular magnetic field of strength 0.050 T. A 2.0 m length of the bundle lies within the magnetic field, as shown. Determine the magnitude and direction of the magnetic force on the current-carrying bundle.





The current is perpendicular to the magnetic field so there will be a force present.

Since the bundle has 10 wires, $n = 10$.

$F = nILB = 10 \times 10 \times 2.0 \times 0.050 = 10$ N

To find direction, use the right-hand rule with thumb pointing right to represent current and fingers pointing into the page. The palm (and force) points up the page.

Therefore, the magnetic force on the current-carrying wire is 10 N upwards.

Theory summary

- A magnetic force will be experienced by a charged particle when it is moving at an angle to a magnetic field.
  - $F = qvB$ for motion which is perpendicular to the magnetic field.
  - There is no magnetic force if the direction of motion is parallel to a magnetic field.
- The direction of the magnetic force is perpendicular to both the direction of motion of the charged particle and the magnetic field.
  - The direction of the force is determined using the right-hand palm rule.
  - For negative charges, point the thumb in the opposite direction to the motion.
  - A charged particle which moves perpendicular to a magnetic field will follow a circular path with radius $r = \frac{mv}{qB}$.
- A magnetic force is experienced by a current-carrying wire in a magnetic field when the current flows at an angle to the field.
  - $F = nILB$ for current which is perpendicular to the magnetic field.
  - There is no magnetic force if the current is parallel to the magnetic field.
- The direction of the magnetic force on a current-carrying wire is determined by the right-hand palm rule, where the thumb represents the direction of conventional current (the direction positive charges would flow).

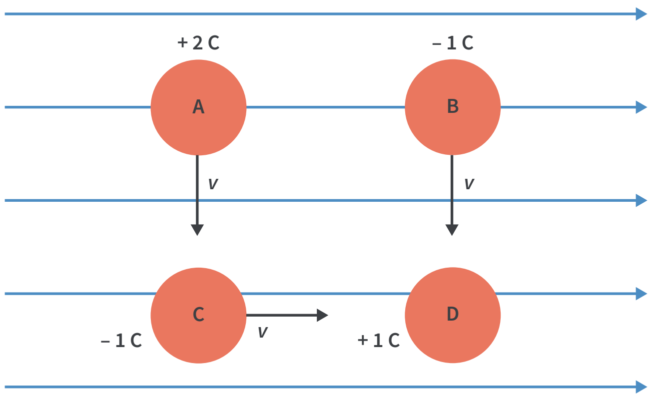
KEEN TO INVESTIGATE?

oPhysics 'Charged Particle in a Magnetic Field' simulation
https://ophysics.com/em7.html

6C Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–5.



Four charged particles are inside a magnetic field. Particles *A*, *B*, and *C* are moving with directions shown in the diagram.

Question 1

Will there be a magnetic force exerted on particle *A*?

Question 2

Will there be a magnetic force exerted on particle *C*?

Question 3

Will there be a magnetic force exerted on particle *D*?

Question 4

The path of particle B within the magnetic field will be

A linear.

B parabolic.

C circular.

D unpredictable.

Question 5

Which particle will experience the magnetic force with the greatest magnitude? Assume that all the pictured velocity vectors have equal magnitude.

Question 6

The direction of the magnetic force on a current-carrying wire with current flowing perpendicular to a magnetic field is the same as the direction of the magnetic force on (select all that apply).

A an electron moving in the same direction as the current.

B an electron moving in the opposite direction to the current.

C a proton moving in the same direction as the current.

D a proton moving in the opposite direction to the current.

E an electron moving in a direction perpendicular to the current.

Question 7

Which right-hand rule is used to determine the direction of the magnetic force on a charged particle moving perpendicular to a magnetic field?

A Right-hand coil rule

B Right-hand curl rule

C Right-hand palm rule

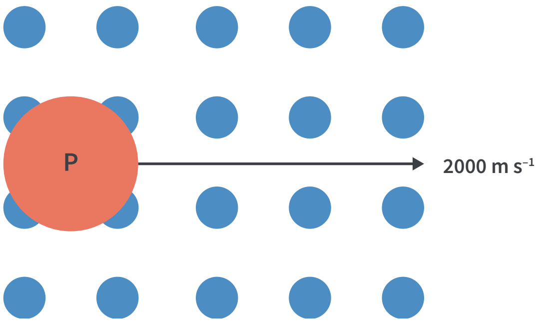
D None of the above

EXAM-STYLE QUESTIONS

This lesson

Question 8 (4 MARKS)

A proton is moving to the right at 2000 m s^{-1} and enters a uniform magnetic field of $B = 0.030$ T, as shown. The charge of a proton is $+1.6 \times 10^{-19}$ C.



a Determine the magnitude of the magnetic force experienced by the proton. (2 MARKS)

b Determine the direction of the magnetic force experienced by the proton. (1 MARK)

c Determine the direction of the magnetic force if the proton was replaced by an electron with the same velocity. (1 MARK)

Question 9 (3 MARKS)

An electron moving perpendicular to a magnetic field experiences a magnetic force of 2.00×10^{-11} N. Take the magnetic field strength to be 3.00 T, the charge of an electron to be -1.6×10^{-19} C, and the mass of an electron to be 9.1×10^{-31} kg.

a Show that the speed of the electron within the magnetic field is 4.2×10^{7} m s^{-1}, ignoring relativistic effects. (1 MARK)

b Calculate the radius of the path of this electron. Show your working. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q1

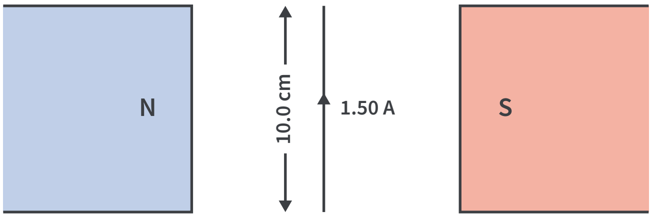
Question 10 (2 MARKS)

Explain why a charged particle moving perpendicular to a uniform magnetic field will always travel in a circular path, assuming that no other forces are present.

Adapted from 2018 VCAA NHT Exam Section B Q3

Question 11 (2 MARKS)

A current-carrying wire runs between the opposite poles of two bar magnets. The length of wire within the magnetic field is 10.0 cm, and it carries a current of 1.50 A upwards. The magnetic field strength is 0.400 T.

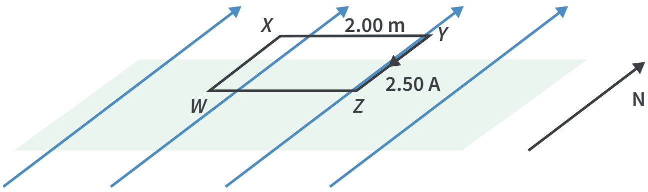


a Determine the magnitude of the force on the current-carrying wire. (1 MARK)

b Determine the direction of the force on the current-carrying wire. (1 MARK)

Question 12 (5 MARKS)

2.50 A of current is flowing around the 10 turn current-carrying loop *WXYZ*. Each side of the loop is 2.00 m long. The loop is within the Earth's magnetic field at a point where the magnetic field lines are parallel to the Earth's surface and point geographically north. The field strength at this point is 6.50×10^{-6} T.



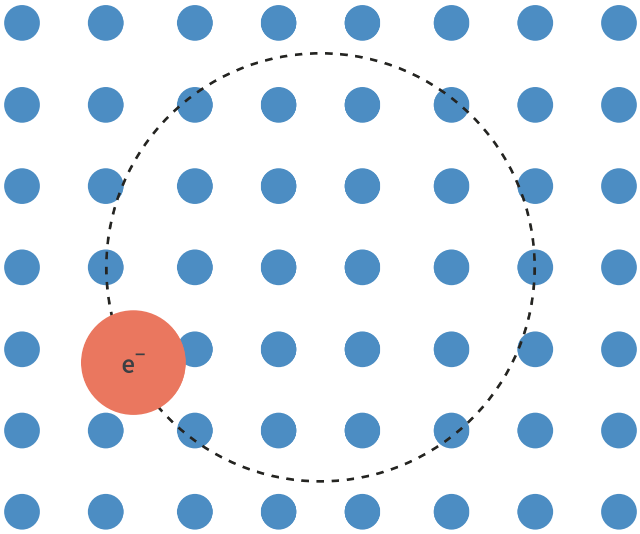
a Which side(s) of the loop experience a magnetic force? (1 MARK)

b Determine the magnitude of the force exerted on each of the side(s) of the loop experiencing a magnetic force. (2 MARKS)

c Determine the direction of the force exerted on each of the side(s) of the loop experiencing a magnetic force. (2 MARKS)

Question 13 (1 MARK)

An electron is undergoing circular motion within a magnetic field which is directed out of the page.



What is the direction of the electron's motion around the circular path shown?

A Clockwise

B Anticlockwise

C The electron can move clockwise or anticlockwise.

D Not enough information to determine.

Question 14 (3 MARKS)

A magnetic field causes an electron to follow a circular path. Moving at a speed of 2.5×10^5 m s^{-1}, the electron path has a radius of 1.0 m. Take the mass of an electron to be 9.1×10^{-31} kg and the charge -1.6×10^{-19} C. Ignore relativistic effects.

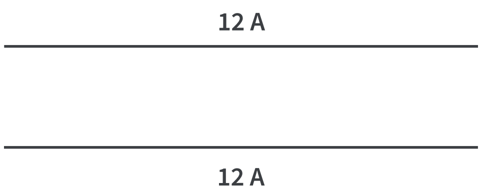
a What is the strength of the magnetic field? (2 MARKS)

b What is the magnitude of the acceleration experienced by the electron? (1 MARK)

Adapted from 2015 VCAA Exam Section B Detailed study 4 Q5

Question 15 (6 MARKS)

Two current-carrying wires are placed close to each other. They each carry a current of 12 A.



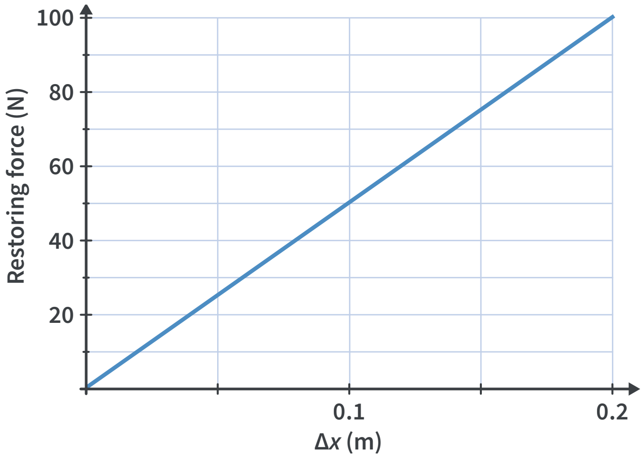
a Determine whether the wires are attracted or repelled from each other when they carry a current in the same direction. Justify your answer with a sketch of the field and force directions in this scenario. (3 MARKS)

b Determine whether the wires are attracted or repelled from each other when they carry a current in the opposite direction. Justify your answer with a sketch of the field and force directions in this scenario. (3 MARKS)

Previous lessons

Question 16 (2 MARKS)

The restoring force of an elastic band is measured at a range of extensions from its equilibrium position.



Assuming that this elastic band can be approximated as an ideal spring, determine the spring constant, k, of the band.

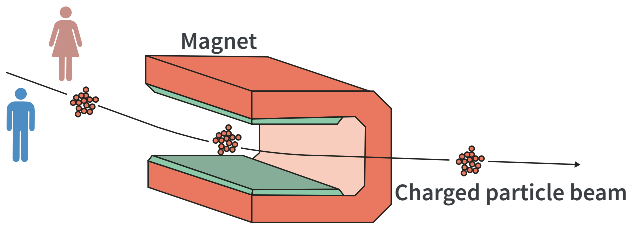
Question 17 (2 MARKS)

A 6500 kg satellite launched by SpaceX is travelling at 6900 m s^{-1} and it orbits at an altitude of 2000 km above the Earth's surface. Determine the magnitude of the centripetal acceleration experienced by the satellite. Take the Earth's radius to be 6.37×10^6 m.

Key science skills

Question 18 (3 MARKS)

Izzy and Keegan are using a uniform magnetic field to bend a beam of charged particles. The young scientists are trying to determine the effect of the magnitude of the charge of the particles on the radius of the beam's path within the magnetic field.



Determine an independent, dependent, and a controlled variable within this experiment.

6D DC MOTORS

DC motors can be seen in many applications across industry and within household appliances, but how does a cordless drill convert the energy stored within its battery into rotation? This lesson will build upon previous lessons from this chapter to explore the operation and principles behind DC motors.

6A Electric fields	6B Magnetic fields	6C Magnetic forces on charged particles	6D DC motors

Study design key knowledge dot point

- investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator

Key knowledge units

DC motor operation	3.1.13.1
Split ring commutators in motors	3.1.13.2

Formulas for this lesson

Previous lessons		New formulas
6C	* $F = nILB$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

DC (direct current) electricity electricity with a constant direction of current and voltage

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation

DC motor operation 3.1.13.1

OVERVIEW

A DC motor utilises the force on a current-carrying conductor ($F = nILB$) within a magnetic field to produce a turning effect (or torque). DC motors convert electrical energy into kinetic energy in the form of rotation.

THEORY DETAILS

A simple DC motor consists of:

- a constant DC voltage supply - which is used to produce a direct current.
- a split ring commutator - which is used to transmit the direct current to the coil in a way that allows continuous rotation.
- a coil of wire - made of one or more windings of a current-carrying conductor which will experience a force due to the magnetic field and is free to rotate.
- a magnetic field - produced by either permanent magnets or electromagnets to create a force on the coil of wire.

The power supply in a DC motor produces a current within the coil that flows from the positive terminal to the negative terminal. This is known as conventional current.

The sides of the coil in a DC motor experience a force with a magnitude given by $F = nILB$, and a direction that can be found by applying the right-hand palm rule to each side that is perpendicular to the magnetic field.

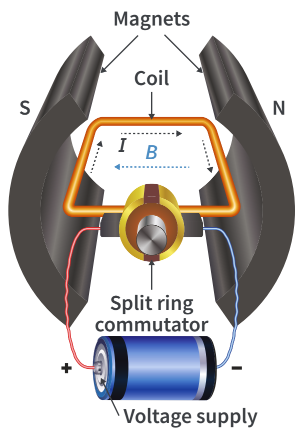


Image: Fouad A. Saad/Shutterstock.com

Figure 1 A simple DC motor showing a voltage supply that provides a direct current via a split ring commutator to a coil of wire situated within the magnetic field of two permanent magnets.

The forces acting on the **sides of the coil that are always perpendicular** to the magnetic field (sides *AB* and *CD* in Figure 2) create a turning effect.

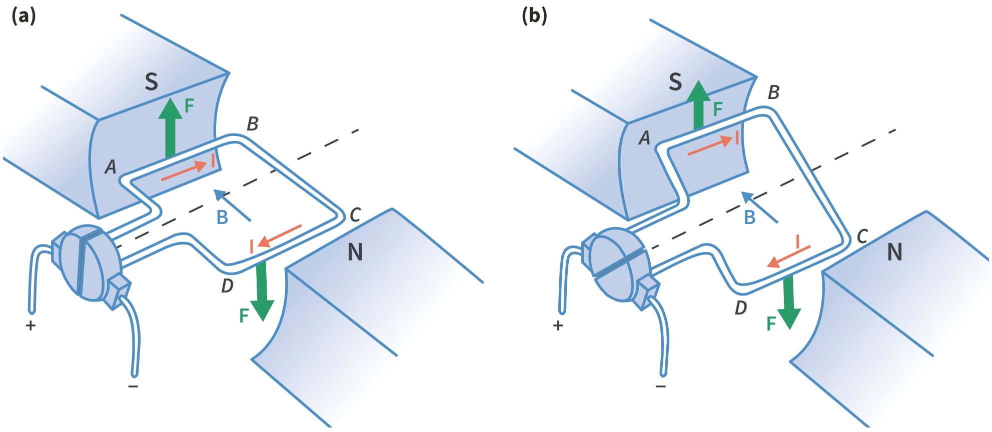


Figure 2 **(a)** Forces on sides *AB* and *CD* act to rotate the coil from the horizontal position. **(b)** The magnitude and direction of the forces on *AB* and *CD* are the same as in (a), but the turning effect decreases as the perpendicular distance to the axis of rotation reduces.

In Figure 2(a) there will be

- an upwards force on side *AB*.
- a downwards force on side *CD*.
- maximum turning effect on the coil.

In Figure 2(b) there will be

- forces of the same magnitude and direction on sides *AB* and *CD* as Figure 2(a).
- a decreased turning effect compared to the horizontal position.

Consider sides *BC* and *DA* of the coil in Figure 2(a). The current flowing through these sides of the coil is parallel to the magnetic field and so there will be no magnetic force acting on these sides when the coil is in the horizontal position. Although the magnitude of the force on these sides increases as the coil rotates towards a vertical position, they never create a turning effect so they can be ignored when analysing the rotation of the coil.

Table 1 The turning effect of the forces on the different sides of a coil as it rotates through horizontal, intermediate, and vertical positions.

	Horizontal position		Intermediate position		Vertical position	
	Force	**Turning effect**	**Force**	**Turning effect**	**Force**	**Turning effect**
AB* and *CD	Constant	Maximum	Constant	Intermediate	Constant	Zero
BC* and *DA	Zero	Zero	Intermediate	Zero	Maximum	Zero

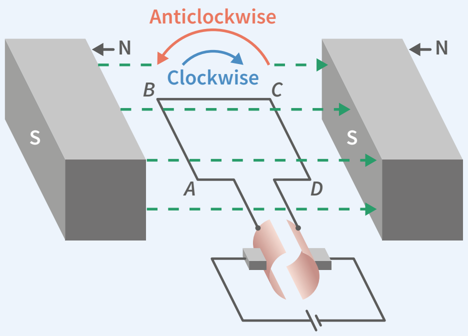
Note that there will briefly be no current in the coil when it is in a perfect vertical position (due to the split ring commutator which is explained in the next section). However this is usually ignored in VCE Physics.

1 Worked example

A simple DC motor is constructed using 150 turns of wire in a square shape with 7.5 cm side lengths. Permanent magnets produce a magnetic field with a strength of 2.5×10^{-2} T. A current of 2.0 A flows through the coil. Determine

a **the magnitude and direction of the force on side *AB*.**

b **the direction of rotation of the coil as viewed from the split ring commutator (clockwise or anticlockwise).**



a $F = nILB = 150 \times 2.0 \times 7.5 \times 10^{-2} \times 2.5 \times 10^{-2} = 0.56$ N

The current flows from *A* to *B* and the magnetic field points to the right. By the right-hand palm rule, the force on side *AB* acts downwards.

$F = 0.56$ N downwards

b By the right-hand palm rule the force on *AB* acts downwards, and the force on *CD* acts upwards. This causes an anticlockwise rotation of the coil when viewed from the split ring commutator.

Split ring commutators in motors 3.1.13.2

OVERVIEW

The split ring commutator in a DC motor acts to reverse the direction of the current within the coil every half rotation, at the vertical position. This reverses the direction of the force on each side of the coil so that the direction of rotation is constant.

THEORY DETAILS

A split ring commutator and the brushes with which it makes contact allow for the continuous rotation of the motor in one direction.

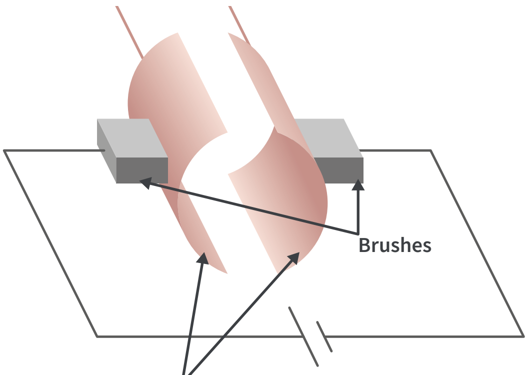


Figure 3 The structure of a split ring commutator in contact with the circuit via brushes.

A split ring commutator changes the direction of the current in the coil every half rotation by changing the connection of the coil to the external circuit when in the vertical position, as seen in Figure 4(b) and (c).

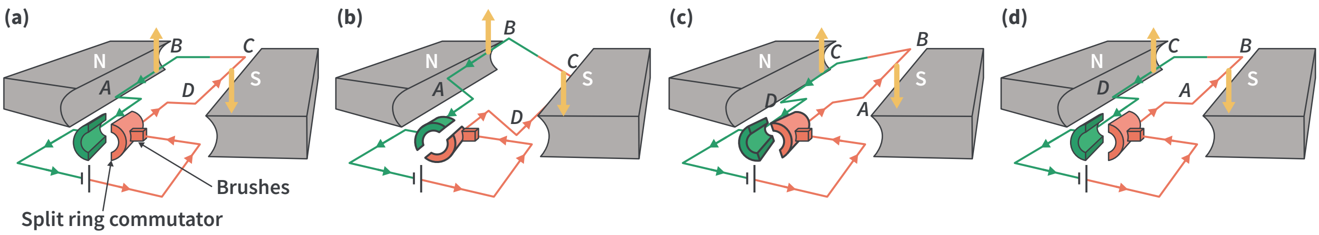


Figure 4 **(a)** The direction of the forces on the coil are determined by the right-hand palm rule. **(b)** As the coil rotates, the direction and magnitude of the force stays the same. **(c)** As the coil passes the vertical position, the split ring commutator will engage the opposite brush of the external circuit. **(d)** The position of the coil after 180° of rotation.

As the split ring commutator engages the opposite side of the external circuit, it acts to reverse the current in the coil and, as a result, produce a force in the opposite direction as shown in Figure 5.

- In Figure 5(a) and (b), the current flows out of the page through the side *AB* and the direction of the force is upwards. The coil rotates clockwise.
- Between Figure 5(b) and (c), the coil passes the vertical position. The direction of the current is reversed (notice the ⊙ changes to a ⊗) so the direction of the force on side *AB* changes from upwards to downwards.
- This means that the turning effect will consistently act in a clockwise direction so that the coil can continue rotating.

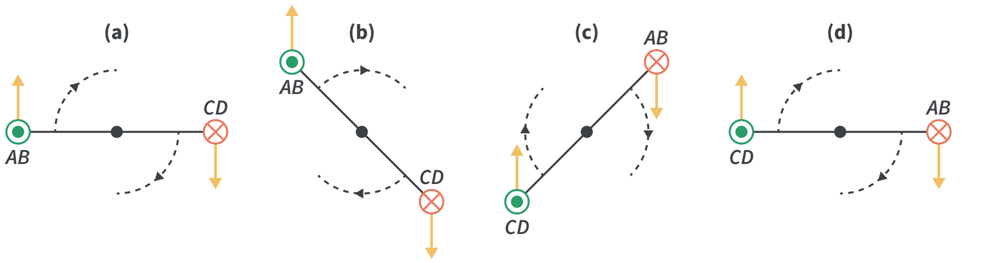


Figure 5 The coil in the DC motor from Figure 4 as it rotates, viewed from the position of the split ring commutator. The direction of the current and the force on each side is shown. The magnetic field, which **points to the right**, is not shown.

Slip rings in DC motors

Slip rings should not be confused with split ring commutators. Slip rings allow parts of a circuit to rotate relative to each other while maintaining a constant electrical connection. They consist of two adjacent rings. A wire from each side of the coil can slide around the inside of one of the rings, maintaining a constant electrical connection (without making contact with the other ring).

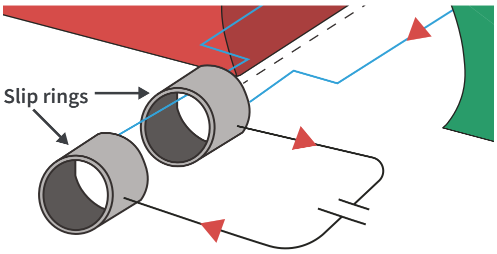


Figure 6 The structure of slip rings

If used in a DC motor, slip rings do **not** reverse the current in the coil like split rings. This means that the direction of the turning effect will alternate when the coil reaches the vertical position. Hence, the coil will oscillate about the vertical position before coming to rest in that position.

The appropriate use of slip rings in the context of alternators (AC generators) will be explained in lesson 7C, but it is important to understand that a DC motor cannot function properly with slip rings.

Theory summary

- A DC motor converts electrical energy into kinetic energy.
- DC motors use current flowing through a coil of wire within a magnetic field to produce a turning effect (or torque) acting on the coil.
  - The magnitude of the force on each side of the coil which is perpendicular to the magnetic field can be calculated from $F = nILB$.
  - The direction of the turning effect is found using the right-hand palm rule on each side.
- DC motors use split ring commutators to
  - reverse the direction of the current in the coil every half rotation.
  - cause the direction of the force acting on the wires in the coil to reverse every half rotation.
  - allow the motor to rotate in a constant direction.
- A DC motor will not be able to complete full rotations if slip rings are used instead of a split ring commutator. The motor will oscillate and then get stuck in the vertical position (assuming a horizontal magnetic field).

KEEN TO INVESTIGATE?

oPhysics 'DC motor' simulation
https://ophysics.com/em10.html

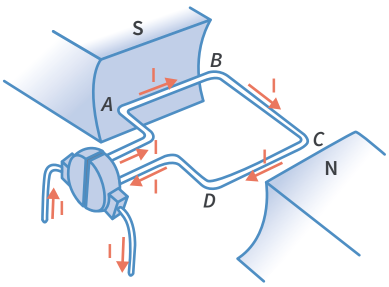
YouTube video: Learn Engineering – DC Motor, How it works?
https://youtu.be/LAtPHANEfQo

6D Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–4.

The figure shows a standard DC motor within a magnetic field.



Question 1

For the first quarter rotation of the coil, the force on side *AB*

A will always act upwards.

B will always act downwards.

C will switch between acting upwards and downwards.

D will always act perpendicular to the plane of the coil.

Question 2

When rotating from the horizontal position shown to a vertical position, the magnitude of the force on side *AB*

A remains constant.

B increases.

C decreases.

D is zero as it is parallel to the magnetic field.

Question 3

During the rotation of the coil, the magnitude of the force on side *BC*

A is always zero.

B is always greater than zero.

C is zero when the coil is in the vertical position.

D is zero when the coil is in the horizontal position.

Question 4

As viewed from the split ring commutator, what direction will the coil rotate?

A Anticlockwise

B Clockwise

C It will oscillate about the vertical position.

D There is not enough information to know the direction of rotation.

Question 5

Which of the following best describes the purpose of a split ring commutator?

A To maintain a constant connection between the coil and the external circuit.

B To reverse the direction of the current in the coil every quarter rotation.

C To reverse the direction of the current in the coil every half rotation.

D To ensure that the turning effect acts in alternating directions every half rotation.

Question 6

What is the effect of replacing the split ring commutator in a DC motor with slip rings? Assume a horizontal magnetic field.

A The coil will oscillate around the vertical position before coming to rest.

B Slip rings have no effect on the operation of a DC motor.

C The coil will oscillate around the horizontal position before coming to rest.

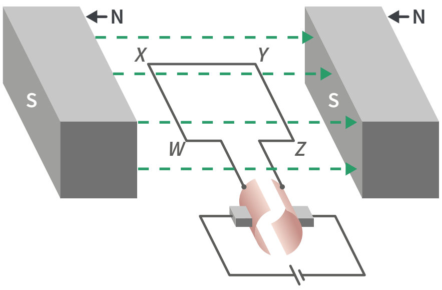
D The coil will not be able to rotate from any position.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (5 MARKS)

Students create a simple DC motor, which is represented in the diagram.



a Which option describes all of the positions during the rotation of the coil when the magnitude of the magnetic force on side *XY* zero? (1 MARK)

- **A** At all positions
- **B** Only in the vertical position
- **C** The position shown
- **D** Any position for which *XY* is horizontal

b Playing with the motor, the students observe that the coil begins moving from rest more easily in some positions compared to others.

What is the best orientation for starting the motor to move from rest? Explain your answer. (2 MARKS)

c The students want to use the motor to power a toy, and need to increase the speed of rotation of the coil.

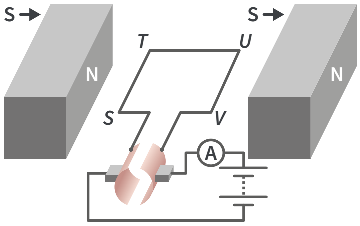
Which of the following changes will increase the speed of rotation? Select all options that apply.
Explain your answer. (2 MARKS)

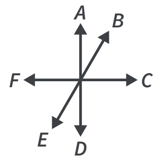
- **A** Increase the resistance of the coil.
- **B** Increase the battery voltage.
- **C** Decrease the number of loops in the coil.
- **D** Reverse the poles of one of the permanent magnets.

Adapted from 2016 VCAA Exam Section B Q14

Question 8 (7 MARKS)

A DC motor is constructed with 80 square loops of wire with a side length of 10 cm and a split ring commutator. The motor's coil sits within a uniform magnetic field of 2.0×10^{-3} T and has a current of 2.5 A.





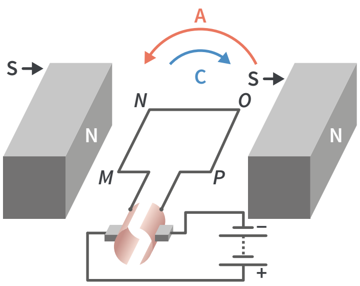
a What is the magnitude and direction (*A-F*) of the force on side *UV* when the loop is in the horizontal position shown. (3 MARKS)

b What is the magnitude and direction (*A-F*) of the force on side *TU* when the loop is in the horizontal position shown. Explain your answer. (2 MARKS)

c Explain the role and operation of the split ring commutator in a DC motor. (2 MARKS)

Question 9 (5 MARKS)

Prior to teaching about DC motors, a teacher shows her students a simple motor which includes a battery and a split ring commutator.



a The teacher positions the coil in the horizontal position shown and turns on the power supply. Will the motor rotate in a clockwise (C) or anticlockwise (A) direction? Explain your answer. (3 MARKS)

b One of her students suggests that by replacing the split ring commutator with slip rings, there will be less friction and the coil will rotate at a faster rate.

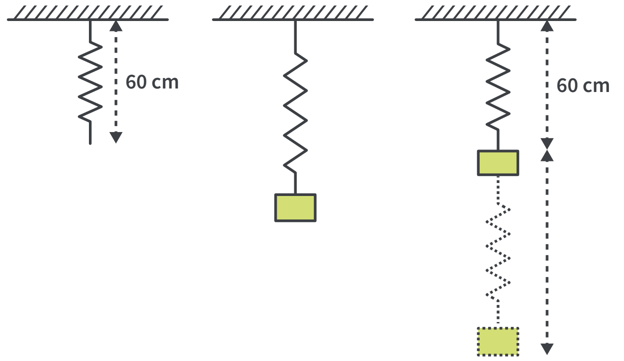
Explain the impact of replacing the commutator with slip rings on the operation of the motor. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q3

Previous lessons

Question 10 (5 MARKS)

Whilst trying to modify his toy gun, Kyle decides he will test the spring used to fire the rubber projectile. The spring has an unstretched length of 60 cm.



Kyle progressively adds 30 g masses to the end of the spring and measures its length when the mass is stationary. He records the included data

Number of 30 g masses on the spring	0	1	2	3
Length of the spring (cm)	60	65	70	75

a Calculate the spring constant. (2 MARKS)

b Kyle now attaches five 30 g masses to the end of the spring and releases it from its unstretched position, allowing the masses to oscillate. Find the **maximum length of the spring**. Ignore frictional losses. (3 MARKS)

Adapted from 2014 VCAA Exam Section A Q2

Question 11 (4 MARKS)

An undiscovered planet has a period of orbit around a star of 7.40×10^5 hours and a radius of orbit of 2.87×10^{12} m.

Using this data, find the mass of the star that the planet orbits.

Adapted from 2014 VCAA Exam Section A Q5

Key science skills

Question 12 (8 MARKS)

Ashleigh uses a variable power supply to change the current supplied to a DC motor and records the resulting period of rotation. She repeats the measurements at each current value five times and then calculates an average value. Her results are displayed in the table. The uncertainty in each average value is ± 0.02 s.

Current (mA)	Average period of rotation (s)
10	0.24 ± 0.02
15	0.20 ± 0.02
20	0.19 ± 0.02
25	0.18 ± 0.02
30	0.16 ± 0.02

a Identify an independent variable, dependent variable, and a controlled variable. (3 MARKS)

b Graph the data collected by Ashleigh on a set of axes. Include:

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

(5 MARKS)

Adapted from 2017 VCAA Exam Section B Q9

CHAPTER 6 QUESTIONS

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

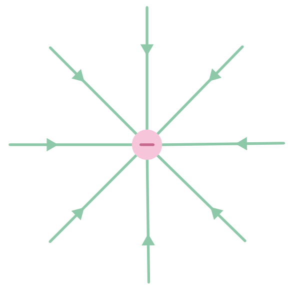
SECTION A

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 diagram shows the field surrounding a stationary negative charge.



This electric field can best be described as

A uniform.

B static.

C parallel.

D uniform and static.

Question 2

The strength of an electric field surrounding a charged object is known to be 6.8×10^{-6} N C^{-1} at a distance *d* from the centre of the object. What is the strength of the electric field at a distance 3*d* from the centre of the object?

A 7.6×10^{-7} N C^{-1} **B** 2.3×10^{-6} N C^{-1} **C** 2.0×10^{-5} N C^{-1} **D** 3.4×10^{-7} N C^{-1}

Question 3

Which of the following correctly associates the type of field to its polar properties?

	Gravitational field	Magnetic field	Electric field
A	Monopole	Dipole	Dipole
B	Dipole	Monopole or dipole	Monopole
C	Monopole or dipole	Monopole	Dipole
D	Monopole	Dipole	Monopole or dipole

Question 4

One way to increase the rotational speed of a **DC motor** is to

A use a coil with a greater resistance.

B use slip rings with less friction.

C increase the current through the coil.

D All of the above

Question 5

An electron enters a uniform electric field of 500 V m^{-1} between two charged plates separated by 15 cm. What is the magnitude and direction of the force exerted on the electron?

A 1.2×10^{-17} N towards the negative plate

B 1.2×10^{-17} N towards the positive plate

C 8.0×10^{-17} N towards the negative plate

D 8.0×10^{-17} N towards the positive plate

SECTION B

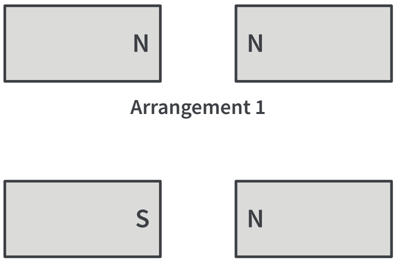
In questions where more than one mark is available, appropriate working must be shown.

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

Question 6 (2 MARKS)

Two bar magnets are positioned in two different arrangements as shown in the diagram. Copy the diagrams. For each arrangement draw **at least four** magnetic field lines to represent the magnetic field. Include arrowheads to show direction.

Adapted from 2016 VCAA Exam Section A Q12



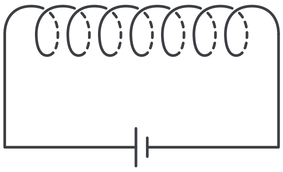
Question 7 (2 MARKS)

Draw the field pattern that exists between a positive point charge and a negative point charge. Use **at least five** electric field lines.

Question 8 (2 MARKS)

On a copy of the diagram shown, draw **five lines** to represent the magnetic field produced by the solenoid. Include arrows to show direction.

Adapted from 2015 VCAA Exam Section A Q15

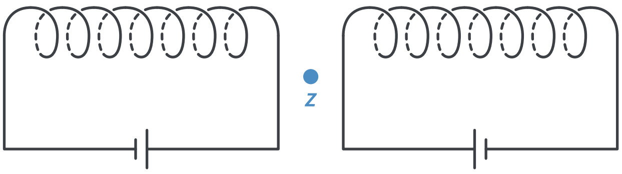


Question 9 (3 MARKS)

Bart builds a house on the equator to test which direction water spirals down a toilet in both hemispheres. To power his equipment, there is a 3.2 m vertical power line on the side of his house which carries 6.6 A of current downwards. The strength of the magnetic field at the equator is known to be 3.1×10^{-5} T horizontally directed towards north. What is the magnitude and direction of the force acting on the power line?

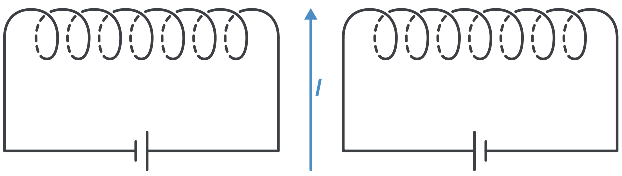
Question 10 (4 MARKS)

A student sets up two solenoids next to each other with their current running in opposite directions. The magnitude of the current is the same in both solenoids. Ignore the Earth's magnetic field in this question.



a If a small magnetic compass needle was placed at point Z, what direction would its north pole point? Explain your answer. (2 MARKS)

b A current-carrying wire is placed vertically between the two solenoids. The current flows up the wire.



What is the direction of the electromagnetic force, if any, on the current-carrying wire? Explain your answer. (2 MARKS)

Adapted from 2017 VCAA NHT Exam Section B Q12

Question 11 (4 MARKS)

A standard DC motor is constructed to be used in John Wick's weaponised clock. A current of 1.75 A flows through the coil which is placed in a uniform magnetic field of 750 mT. It uses 100 square turns of wire.

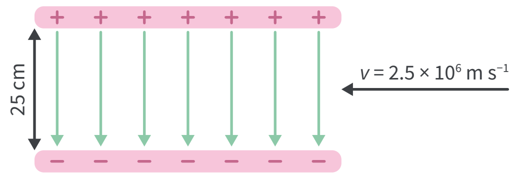
a Given that the force on a side length of the coil which is perpendicular to the magnetic field is 4.0 N, what is the side length of the coil? (2 MARKS)

b In order to make the weaponised clock more lethal, John Wick suggests that the split ring commutator on the DC motor should be replaced by slip rings. Explain the effect that replacing the commutator with slip rings would have on the operation of the motor, if no other change was made. (2 MARKS)

Adapted from 2018 VCAA Exam Section B Q3b

Question 12 (6 MARKS)

Two oppositely charged parallel plates which are 25 cm apart create a uniform electric field of 7.0×10^3 V m^{-1}. An electron is travelling at a speed of 2.5×10^6 m s^{-1} when it enters the field halfway between the plates.



a What is the voltage difference between the two plates? (2 MARKS)

b Draw the path of the electron once it enters the electric field. The electron does not leave the uniform field. (2 MARKS)

c Calculate the kinetic energy gained by the electron as it moves through the electric field. (2 MARKS)

Question 13 (4 MARKS)

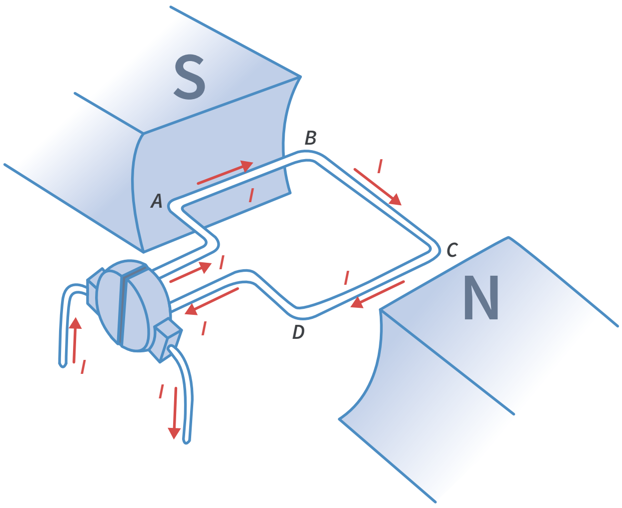
After sliding down a plastic slide, a primary school student has acquired a charge of 4.0×10^{-7} C on the tip of their finger. They are going to use this charge to zap their best friend's nose. Their friend's nose is 2.25 m away from the student's finger. Take $k = 8.99 \times 10^9$ N m^2 C^{-2}.

a Calculate the strength of the electric field due to the student's charged fingertip at their best friend's nose. (2 MARKS)

b Calculate the force that an electron in the best friend's nose experiences due to the student's charged finger. (2 MARKS)

Question 14 (9 MARKS)

In the attempt to build a helicopter and arrive fashionably at the Year 12 formal, Elle designs a simple DC motor. The motor consists of a single square loop of wire with side lengths of 15.0 cm. A current of 3.5 A flows through the loop which is placed within a uniform magnetic field of 45.0 mT.



a What is the size of the force acting on side BC when the loop is in the orientation shown in the diagram? Justify your answer. (2 MARKS)

b Determine the size and direction of the force acting on side *CD*. (3 MARKS)

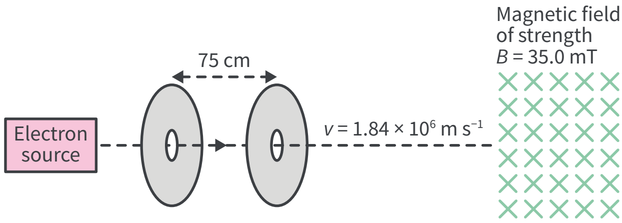
c Explain the function of a split ring commutator in a DC motor. (2 MARKS)

d Elle finds that the motor begins rotating from a stationary position more easily in some orientations rather than others. What is the best orientation(s) of the loop to start the motor? Explain your answer. (2 MARKS)

Question 15 (9 MARKS)

Two plates separated by 75 cm are used to accelerate a proton from rest as shown. The proton leaves the second plate travelling at a speed of 1.84×10^{6} m s^{-1} before entering a uniform magnetic field of 35.0 mT at right angles to its path.

Charge on proton	1.6×10^{-19} C
Mass of proton	1.7×10^{-27} kg
Strength of magnetic field	35.0 mT



a What is the voltage difference between the two plates? (3 MARKS)

b Calculate the electric force on the proton between the two metal plates. (2 MARKS)

c Calculate the magnetic force on the proton when it enters the magnetic field. (2 MARKS)

d What is the radius of the path that the proton follows whilst in this magnetic field? (2 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q1

UNIT 3, AOS 1 QUESTIONS

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

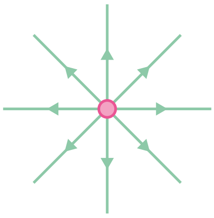
SECTION A

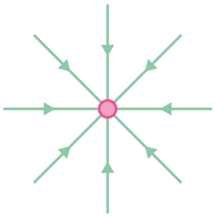
All questions in this section are worth one mark.

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

Question 1

Diagrams 1, 2, and 3 represent different types of fields.


(1)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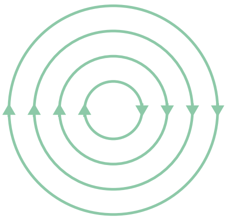

(3)

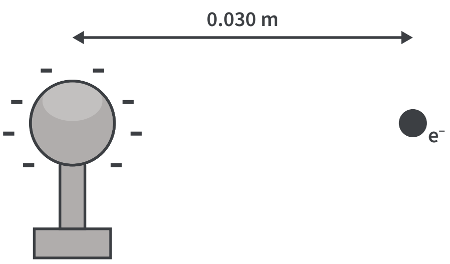
Which of the following options could correctly identify the type of field represented by each diagram?

	Diagram 1	Diagram 2	Diagram 3
A	Electric or gravitational field	Electric field	Magnetic field
B	Electric field	Magnetic field	Gravitational field
C	Electric field	Electric or gravitational field	Magnetic field
D	Magnetic field	Gravitational field	Electric field

Adapted from 2017 Sample VCAA Exam Section A Q2

Use the following information to answer Questions 2 and 3.

A Van de Graaff generator, pictured in the diagram, consists of a small charged sphere.



This particular Van de Graaff generator has a charge of -2.0×10^{-7} C. Take Coulomb's constant to be $k = 9.0 \times 10^{9}$ N m^{-2} C^{-2}.

Adapted from 2018 VCAA NHT Exam Section A Q3

Question 2

Which of the following gives the magnitude of the electric field due to the charge on the generator at the position of the electron shown in the diagram?

A 2.0×10^{6} V m^{-1}

B 4.4×10^{6} V m^{-1}

C 2.0×10^{4} V m^{-1}

D 4.4×10^{4} V m^{-1}

Question 3

Which of the following gives the direction of force on the electron?

A Left

B Right

C Into the page

D Out of the page

Question 4

Mass of Vesta	2.59×10^{20} kg
Radius of Vesta	2.63×10^{5} m
Universal gravitational constant, G	6.67×10^{-11} N m^2 kg^{-2}

The gravitational field strength at the surface of Vesta is closest to

A 0.13 N kg^{-1}.

B 0.22 N kg^{-1}.

C 0.25 N kg^{-1}.

D 26 N kg^{-1}.

Adapted from 2018 VCAA NHT Exam Section A Q2

Question 5

The gravitational field strength at the surface of Enceladus is 0.113 N kg^{-1}.

Which one of the following is the closest to the change in gravitational potential energy when a 30 kg mass falls from 5.0 m above Enceladus to the surface of Enceladus?

A 16 J

B 17 J

C 18 J

D 19 J

Adapted from 2019 VCAA NHT Exam Section A Q4

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)

Three point charges are lined up horizontally.

a Draw the electric field between the three point charges using six field lines. (2 MARKS)

b Identify whether the field between the three charges is uniform or non-uniform. (1 MARK)

Adapted from 2017 VCAA Exam Section B Q1

Question 7 (5 MARKS)

According to one model of the atom, an electron moves around a single proton in a hydrogen atom in a circular orbit. To model an atom, students used a large positively charged metal sphere as the proton, and a smaller negatively charged sphere as the electron. The smaller sphere was placed on the desk, freely able to orbit around the larger sphere at a distance of 5.3 cm. Take the magnitude of the charge on the two spheres to be 2.4×10^{-6} C, and $k = 9.0 \times 10^{9}$ N m^2 C^{-2}.

a Determine the magnitude of the electric field due to the larger sphere at a distance of 5.3 cm. Show your working. (2 MARKS)

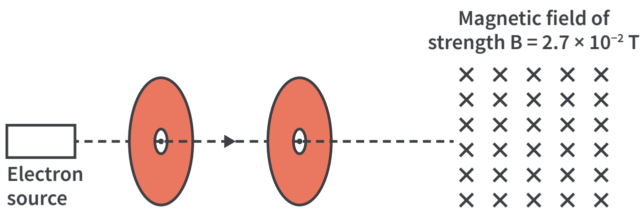
b Take the force acting on the smaller sphere by the larger sphere to be 18.5 N. Hence, calculate the speed of the smaller sphere in its circular path. Take the mass of the smaller sphere to be 25 g. (3 MARKS)

Adapted from 2017 VCAA Exam Section B Q2

Question 8 (5 MARKS)

Electrons are accelerated from rest between two plates.

Mass of electron	9.1×10^{-31} kg
Charge on electron	-1.6×10^{-19} C
Electric field strength	2×10^{-2} V m^{-1}
Accelerating voltage	14 mV



a Calculate the speed of an electron as it exits the electric field. Show your working. (2 MARKS)

b Calculate the distance between the two plates. Show your working. (2 MARKS)

The electrons enter a region of uniform magnetic field with strength $B = 2.7 \times 10^{-2}$ T that is at right angles to their paths as shown in the diagram.

c Draw the path of an electron travelling through the uniform magnetic field. (1 MARK)

Adapted from 2019 VCAA NHT Exam Section B Q1

Question 9 (7 MARKS)

A uniform electric field accelerates protons from rest to a speed of 5.00×10^{7} m s^{-1}. The protons then pass into a region of uniform magnetic field at right angles to their velocity. The strength of the uniform magnetic field is 500 mT.

Mass of proton	1.67×10^{-27} kg
Charge on proton	$+1.60 \times 10^{-19}$ C

a Explain why the path the protons take through the magnetic field is circular in shape. (3 MARKS)

b What is the radius of curvature of the protons in the magnetic field? (2 MARKS)

c Calculate the magnitude of the magnetic force on the protons. (2 MARKS)

Adapted from 2018 VCAA NHT Exam Section B Q3

Question 10 (9 MARKS)

A spacecraft is in orbit at an altitude of 8.39×10^{5} m above the surface of Mars. The mass of Mars is 6.4×10^{23} kg and its radius is 3.4×10^{6} m. The mass of the spacecraft is 4.3×10^{4} kg. Take the universal gravitational constant, G, to be 6.67×10^{-11} N m^2 kg^{-2}.

a Calculate the spacecraft's period of orbit around Mars. (4 MARKS)

The altitude above the surface of Mars is halved so that the spacecraft is now in a new stable orbit.

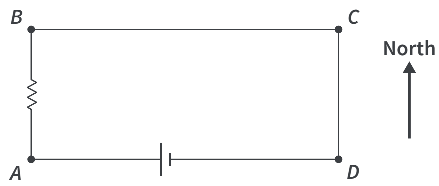
b Will the speed of the spacecraft need to be greater, the same, or lower in this new orbit? Explain your reasoning. (2 MARKS)

c Will this increase, decrease, or have no effect on the gravitational potential energy of the satellite? Take the surface of Mars as the zero of gravitational potential energy. Justify your answer. (3 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q10

Question 11 (5 MARKS)

A heavy duty electric circuit is set up.



The circuit carries a current of 958 A and lies within Earth's magnetic field. At the point of measurement, the Earth's magnetic field is horizontally north and its strength is 8.0×10^{-5} T.

a What is the direction of the force on wire *BC*? (1 MARK)

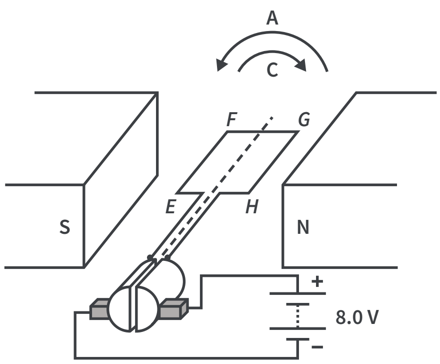
b What is the magnitude of the force on each metre of wire between *B* and *C*? (2 MARKS)

c What is the magnitude of the force acting on side *CD*? Justify your answer. (2 MARKS)

Adapted from 2019 VCAA Exam Section A Q2

Question 12 (11 MARKS)

A simple DC motor consists of a square loop of wire of side 20 cm and 30 turns, a magnetic field of strength 4.0×10^{-3} T, and a split ring commutator connected to an 8.0 V battery. The current in the loop is 1.5 A.



a The motor is set with coils horizontal, as shown, and the power source is turned on. Will the motor rotate clockwise or anticlockwise? Explain your answer. (3 MARKS)

b What is the magnitude of the net force acting on the motor? (1 MARK)

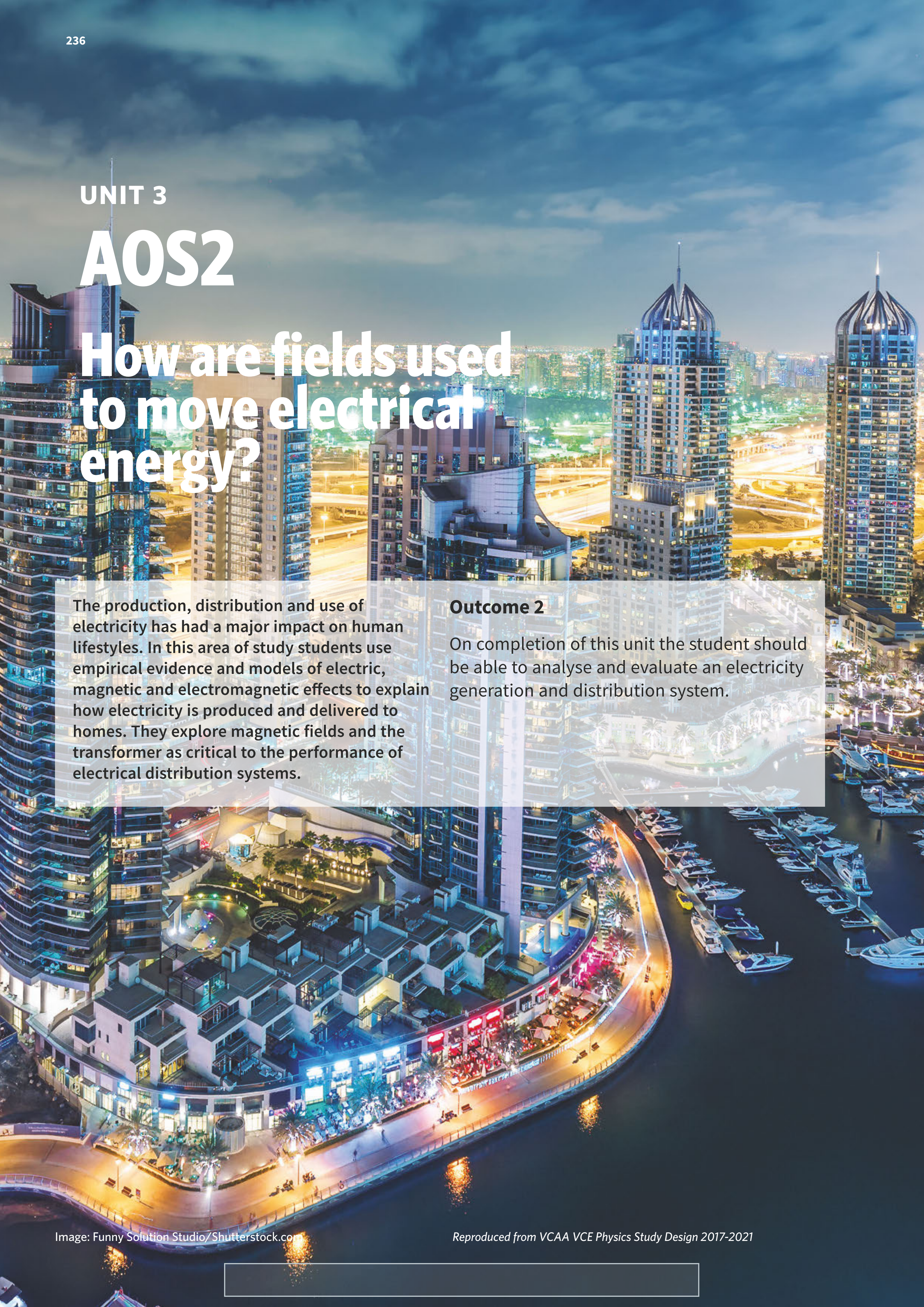
c Calculate the magnitude of the force on side *EF*. (2 MARKS)

d Determine the magnitude of the force on side *FG* in the position shown. (1 MARK)

e Explain the role of the split ring commutator in a DC motor. (2 MARKS)

f Explain the effect that replacing the split ring commutator with slip rings would have on the operation of the motor, if no other change was made. (2 MARKS)

Adapted from 2013 VCAA Exam Section A Q16



UNIT 3

AOS2

How are fields used to move electrical energy?

The production, distribution and use of electricity has had a major impact on human lifestyles. In this area of study students use empirical evidence and models of electric, magnetic and electromagnetic effects to explain how electricity is produced and delivered to homes. They explore magnetic fields and the transformer as critical to the performance of electrical distribution systems.

Outcome 2

On completion of this unit the student should be able to analyse and evaluate an electricity generation and distribution system.

Image: Funny Solution Studio/Shutterstock.com

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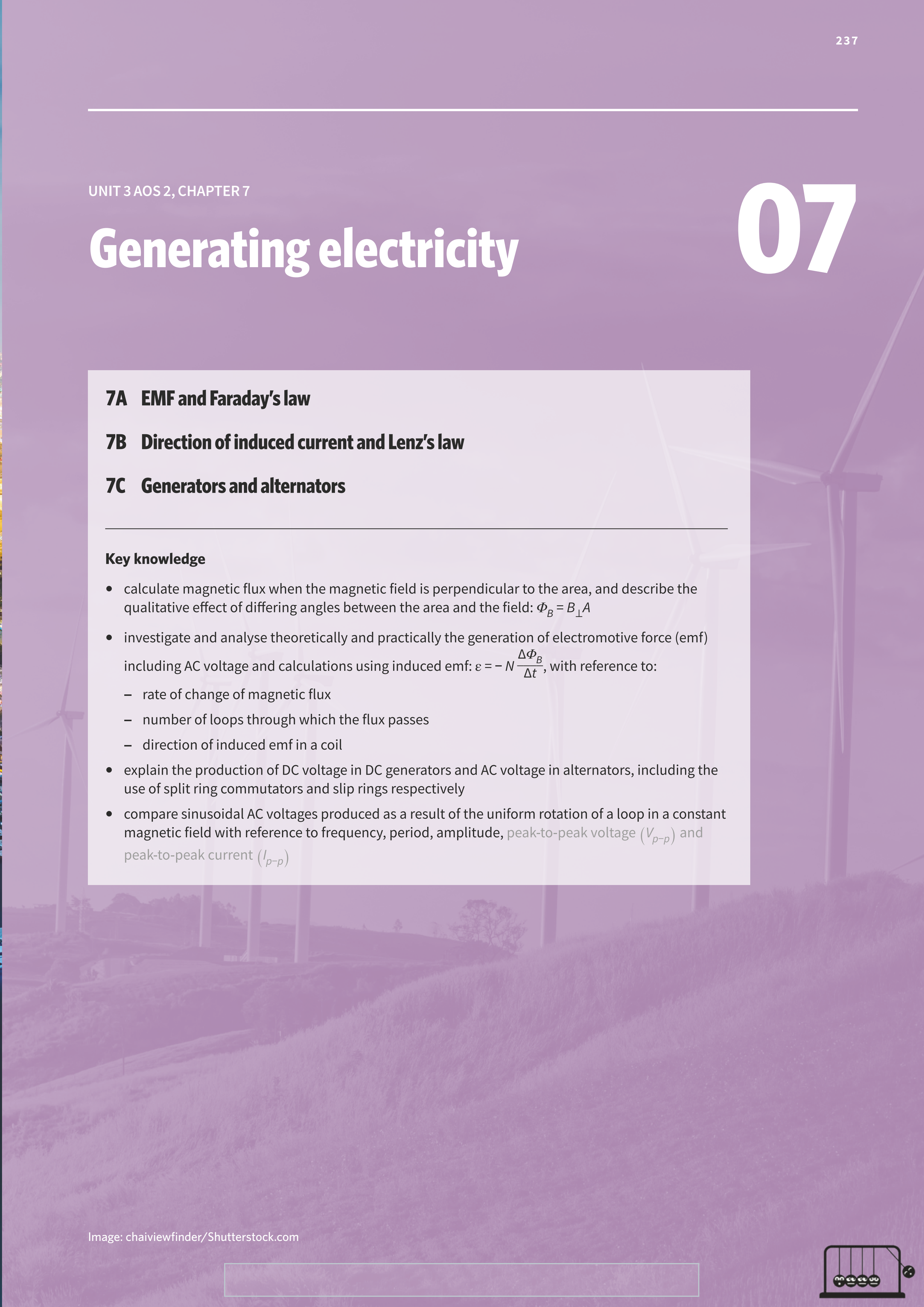


UNIT 3 AOS 2, CHAPTER 7

Generating electricity

07

Key knowledge

- calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field: $\Phi_B = B_{\perp}A$
- investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced emf in a coil
- explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively
- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})

7A EMF AND FARADAY'S LAW

In chapter 6, we learned how charges can experience a force under particular conditions due to the presence of a magnetic field. This principle can be used to generate electrical energy in the form of a voltage and an associated electric current. This lesson will introduce magnetic flux and the electromotive force (EMF), which is induced when the magnetic flux through a conducting loop changes.

7A EMF and Faraday's law	7B Direction of induced current and Lenz's law	7C Generators and alternators

Study design key knowledge dot points

- calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field: $\Phi_B = B_\perp A$
- investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced emf in a coil

Key knowledge units

Magnetic flux	3.2.1.1
Faraday's law	3.2.2.1

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $\Phi_B = B_\perp A$
	* $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

electromagnetic induction the production of an electromotive force (EMF) due to the change in magnetic flux through a conducting loop

electromotive force (EMF) the voltage created or supplied due to energy being transformed into electrical potential energy

magnetic flux a measure of the amount of magnetic field lines passing through an area

magnetic flux density the amount of magnetic flux per unit area. Equivalent to magnetic field strength

Magnetic flux 3.2.1.1

OVERVIEW

Magnetic flux describes the amount of magnetic field flowing through a given area. The area, magnetic field strength, and the angle between the area and the field lines determine the magnitude of the magnetic flux.

THEORY DETAILS

The magnetic flux through a surface (such as a loop or coil of wire) is the amount of magnetic field passing through the area of that surface. The unit of magnetic flux is the weber (Wb).

$$\Phi_B = B_{\perp} A$$

Φ_B = magnetic flux (Wb), B = magnetic field strength (T), A = area perpendicular to the magnetic field (m^2)

The magnetic flux can be visualised as the number of magnetic field lines that pass through a given area. Figure 1 depicts three surfaces in three magnetic fields. We will compare the magnetic flux for the surface on the top and in the middle:

- The surfaces on the top and in the middle have the same area ($A_1 = A_2$).
- The magnetic field strength on the top is greater than the magnetic field strength in the middle ($B_1 > B_2$). This is represented by field lines that have closer spacing on the top than in the middle.
- Hence, the magnetic flux through the surface on the top is greater than the magnetic flux through the surface in the middle ($\Phi_{B1} > \Phi_{B2}$). This is represented by a greater number of field lines passing through the surface on the top than the middle.

Now consider the surfaces in the middle and on the bottom of Figure 1.

- The surface in the middle has a greater area than the surface on the bottom ($A_2 > A_3$).
- The magnetic field strength in the middle is equal to the magnetic field strength on the bottom ($B_2 = B_3$). This is represented by field lines that have the same spacing in the middle and on the bottom.
- Hence, the magnetic flux through the surface in the middle is greater than the magnetic flux through the surface on the bottom ($\Phi_{B2} > \Phi_{B3}$). This is represented by a greater number of field lines passing through the surface in the middle than on the bottom.

Note that the magnetic field strength, B, can also be referred to as the magnetic flux density.

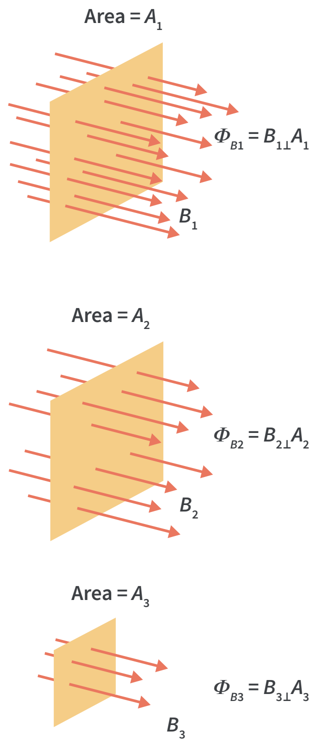


Figure 1 The amount of magnetic flux through a surface is dependent on the magnetic field strength (indicated by the density of the field lines) and the surface area.

Magnetic flux graphs

Magnetic flux graphs are used to show how the magnetic flux through an area changes over time. The magnetic flux through an area will change when either the perpendicular area within the magnetic field changes or the magnetic field strength changes. For example, if a loop moves into and then out of a uniform magnetic field at a constant speed as depicted in Figure 2(a), the perpendicular area of the loop within the field increases and then decreases over time. Figure 2(b) shows the corresponding magnetic flux vs. time graph.

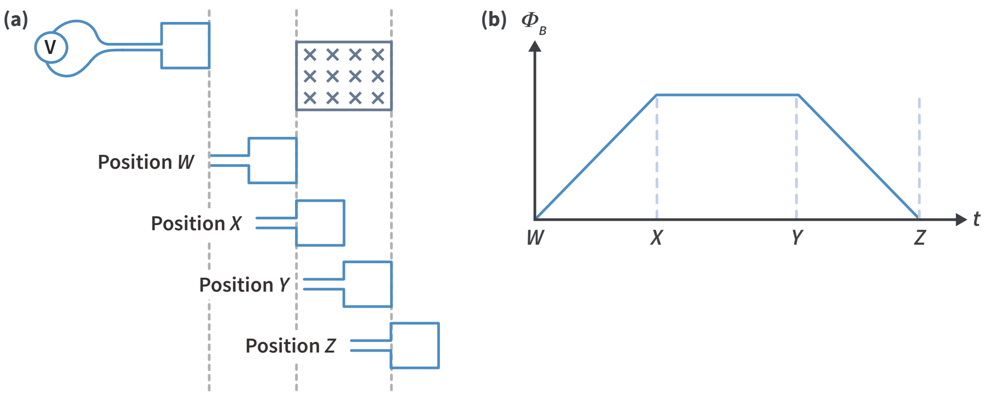


Figure 2 **(a)** A coil of wire that is initially outside of a uniform magnetic field moves at a constant speed entirely into the magnetic field, and then exits the field. **(b)** The magnetic flux-time graph with the corresponding positions (W, X, Y, and Z) shown: the flux increases when the loop passes into the field, is constant while the entire loop is inside the magnetic field, and decreases as it leaves the field.

When the distance between a loop (or a coil) and a bar magnet changes, as shown in Figure 3(a), the magnetic field strength through the loop will change since the magnetic field strength nearer to the magnet is stronger than the field strength further from the magnet. The graph in Figure 3(b) shows the magnetic flux through the coil in Figure 3(a) as the magnet starts from rest at $t = 0$ s and moves through the coil, coming to rest again at $t = 2$ s.

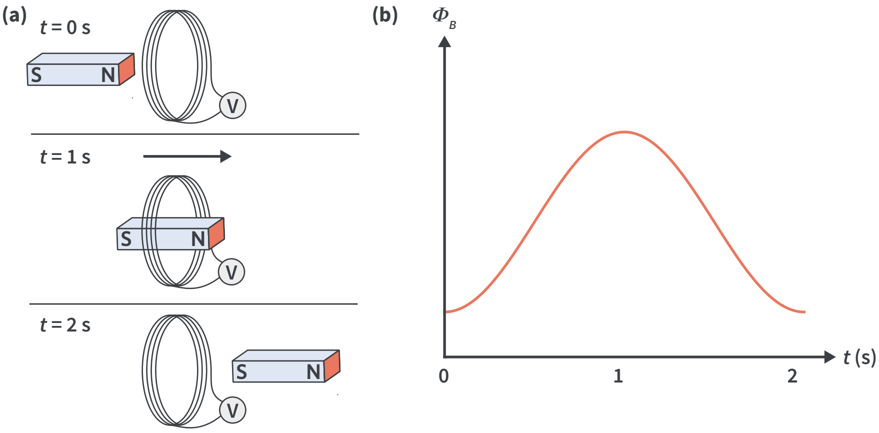


Figure 3 **(a)** A bar magnet starting from rest and moving through a coil of wire, coming to rest again on the other side. **(b)** The magnetic flux-time graph for the coil.

The effect of the angle between the magnetic field and the area on the magnetic flux

Magnetic flux is a maximum when the given area is perpendicular to the magnetic field. When the area is not perpendicular, the **effective** area is reduced because fewer magnetic field lines pass through it. If the area is parallel to the magnetic field, the effective area is zero so the magnetic flux will be zero. This is shown in Figure 4.

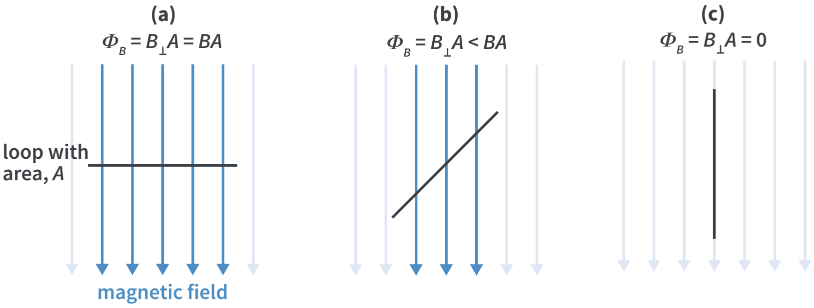


Figure 4 A side-view of a loop as it rotates within a magnetic field. **(a)** The magnetic flux is at a maximum when the loop is perpendicular to the magnetic field. **(b)** The magnetic flux is reduced when the surface is not perpendicular to the magnetic field, and **(c)** is zero when the surface is parallel to the magnetic field.

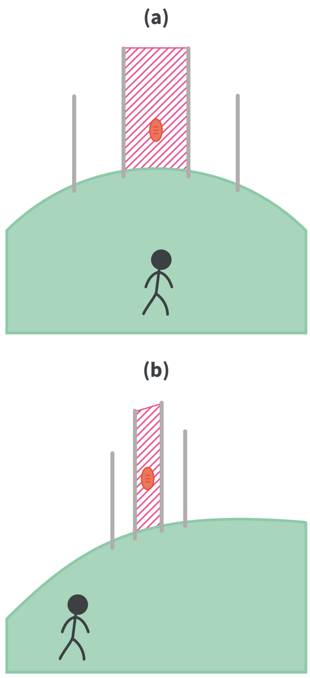


Figure 5 The view of a goal in AFL when the ball is kicked **(a)** from straight in front and **(b)** from an angle

To better understand this, it may help to think about how it is easier to kick a ball through a set of goals from straight in front of the goals than from an angle. This is because the effective area through which the ball must pass to score a goal is reduced when viewed from an angle, as shown in Figure 5.

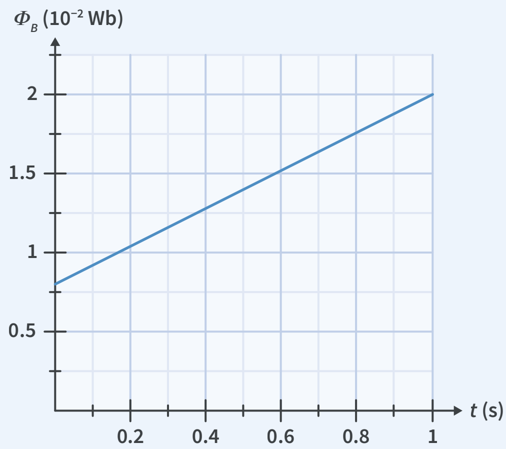
1 Worked example

A circular loop with radius $r = 0.25$ m is placed in a variable magnetic field. The magnetic field increases at a constant rate from 0.040 T at $t = 0$ s to 0.100 T at $t = 1$ s. Draw a magnetic flux-time graph to represent how the flux changes with time.

At $t = 0$ s: $\Phi_B = B_\perp A = B \times \pi r^2 = 0.040 \times \pi \times 0.25^2 = 7.9 \times 10^{-3}$ Wb

At $t = 1$ s: $\Phi_B = B_\perp A = B \times \pi r^2 = 0.100 \times \pi \times 0.25^2 = 2.0 \times 10^{-2}$ Wb

Since the magnetic field increases at a constant rate, the graph is linear between these two points.



Faraday's law 3.2.2.1

OVERVIEW

A changing magnetic flux in a conducting loop or coil induces an electromotive force (equivalent to a voltage) with a magnitude that is proportional to the rate of change of the magnetic flux.

THEORY DETAILS

When the magnetic flux through a loop or coil changes over time there is an induced electromotive force (EMF), which means a potential difference (voltage) is created in the loop. This is known as electromagnetic induction. The greater the rate of change of the magnetic flux, the greater the EMF produced. Faraday's law defines the EMF induced in a coil with N turns as:

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

ε = EMF (V), N = number of turns (no units), $\Delta\Phi_B$ = change in magnetic flux (Wb), Δt = change in time (s)

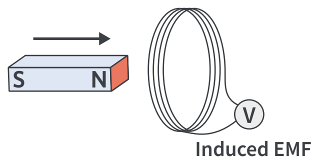


Figure 6 The changing magnetic flux when a magnet moves towards a coil of wire induces an EMF.

An EMF will cause a current to flow in a conducting loop or coil. The negative sign in Faraday's law indicates the direction of the induced EMF and current. For calculation questions in VCE Physics, we will usually be asked to provide the magnitude of the EMF, which means we can disregard the negative sign in the formula. The direction can be determined separately, which will be investigated in lesson 7B.

gradient of Φ_B vs. t graph

$$\varepsilon = -N\boxed{\frac{\Delta\Phi_B}{\Delta t}}$$

Figure 7 EMF is equal to the negative value of N multiplied by the gradient of the Φ_B vs. t graph at corresponding times.

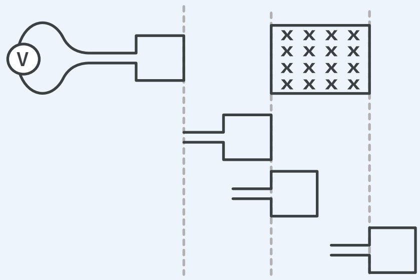
It is common to use magnetic flux vs. time (Φ_B vs. t) graphs and EMF vs. time graphs to represent scenarios where electromagnetic induction occurs (see Worked example 1). Notice that Faraday's law includes the term $\frac{\Delta\Phi_B}{\Delta t}$, which represents the gradient of the Φ_B vs. t graph. The sign of the EMF will be different when the magnetic flux is increasing compared with when the magnetic flux is decreasing, as described by the following rules.

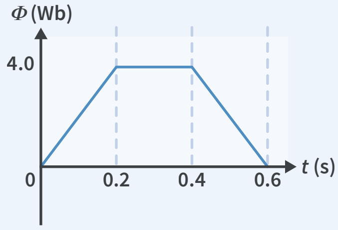
- The EMF graph should be **negative** when the magnetic flux graph has a **positive gradient**.
- The EMF graph should be **positive** when the magnetic flux graph has a **negative gradient**.

Note that these rules follow Faraday's law with the inclusion of the negative sign. However, as mentioned earlier, it is acceptable to exclude the negative sign, which means that a positive EMF could represent an increasing flux and vice versa. The important thing is to be consistent.

2 Worked example

A square loop of 5 turns is moved through a uniform magnetic field. Using the included magnetic flux-time graph, draw a corresponding EMF-time graph.





From $t = 0$ s to $t = 0.2$ s: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -5 \times \frac{4.0-0}{0.2-0} = -100$ V

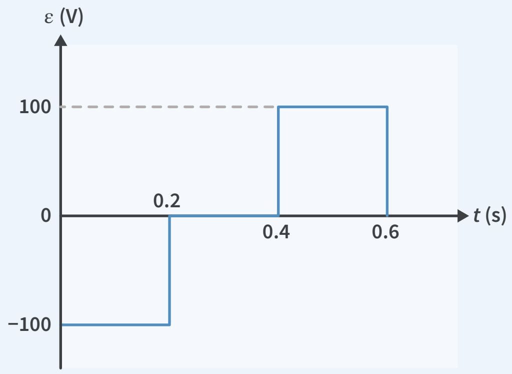
Notice that the gradient for this section of the graph is 20 Wb s^{-1} so we could obtain the same result using $\varepsilon = -N \times gradient = -5 \times 20 = -100$ V.

From $t = 0.2$ s to $t = 0.4$ s: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -5 \times \frac{4.0-4.0}{0.4-0.2} = 0$ V

Notice that the gradient is also zero for this section of the graph.

From $t = 0.4$ s to $t = 0.6$ s: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -5 \times \frac{0-4.0}{0.6-0.4} = 100$ V

Notice that the gradient for this section of the graph is –20 Wb s^{-1} so we could obtain the same result using $\varepsilon = -N \times gradient = -5 \times (-20) = 100$ V.



Note that:

- The sign of the magnetic flux-time graph is arbitrary – it could have been inverted so that all the flux values were negative (with a minimum value of –4.0 Wb).
- The sign of an EMF-time graph should consistently reflect how the magnetic flux is changing. It is good practice to draw a negative EMF when the flux is increasing, and a positive EMF when the flux is decreasing, however an inverted version of the EMF-time graph is acceptable.
- When the magnetic flux-time graph is linear, such as from 0 to 0.2 s, the EMF is constant.
- When the magnetic flux-time graph is flat (horizontal), such as from 0.2 to 0.4 s, the EMF is zero.

The relationship between Faraday's law and the magnetic force on charged particles

The content in this section is not required knowledge for VCE Physics, but it may help to consolidate our understanding of Faraday's law.

In lesson 6C, we learned that a charge that is moving through a magnetic field will experience a magnetic force given by $F = qvB$ if the motion is perpendicular to the magnetic field. Given that a piece of wire consists of many charged particles (protons and electrons in its atoms), when the wire moves in a perpendicular direction through a magnetic field, the charges will experience a magnetic force. The force is greater if the wire (and the charges within it) is moving faster.

Consider Figure 8, in which a wire loop moves into and out of a magnetic field. Although negatively charged electrons are the particles that generally move within a conductor, for simplicity we will model the effect on positive charges, which leads to the same result. By the right-hand palm rule, the positive charges in the wire will experience a force directed up the page as the wire moves to the right through a magnetic field that is into the page.

- In Figure 8(a) the charges in side *XY* experience this force but the charges in side *WZ* do not, so the overall effect is to push the positive charges in an anticlockwise direction. This situation corresponds to an increasing magnetic flux and an induced EMF.
- In Figure 8(b) the charges in sides *XY* and *WZ* experience the same force so there is no overall effect. There is no EMF induced.
- In Figure 8(c) the charges in side *WZ* experience this force but the charges in side *XY* do not, so the overall effect is to push the positive charges in a clockwise direction. This situation corresponds to a decreasing magnetic flux and an induced EMF with the opposite sign to that in Figure 8(a).

The concept of magnetic flux, upon which Faraday's law is based, is a model that we use to simplify this process.

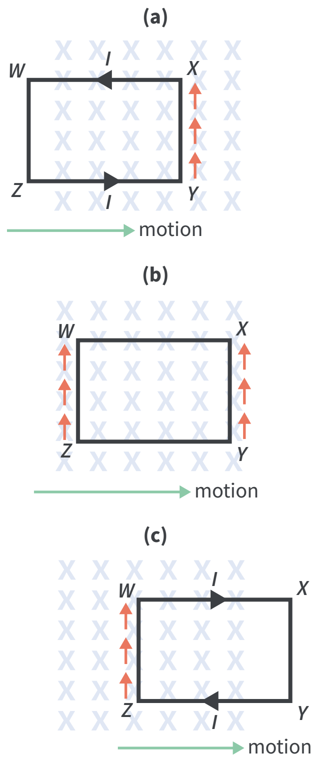


Figure 8 As a wire loop moves through a magnetic field, there is a force on each of the charges within the wire. When the forces are not symmetrical around the wire, which corresponds to the magnetic flux in the wire changing, an EMF will be induced.

Theory summary

- Magnetic flux is a measure of the amount of magnetic field lines passing through an area.
  - $\Phi_B = B_\perp A$
  - Magnetic flux graphs are used to show the change in flux over time.
- A change in magnetic flux induces an EMF (voltage) in a loop or coil.
  - Faraday's law: $\varepsilon = -N\dfrac{\Delta\Phi_B}{\Delta t}$
  - Induced EMF graphs are derived from Φ_B vs. t graphs: the EMF is proportional to the value of the gradient of the Φ_B vs. t graph.

KEEN TO INVESTIGATE?

oPhysics 'Electromagnetic Induction' simulation
https://ophysics.com/em11.html

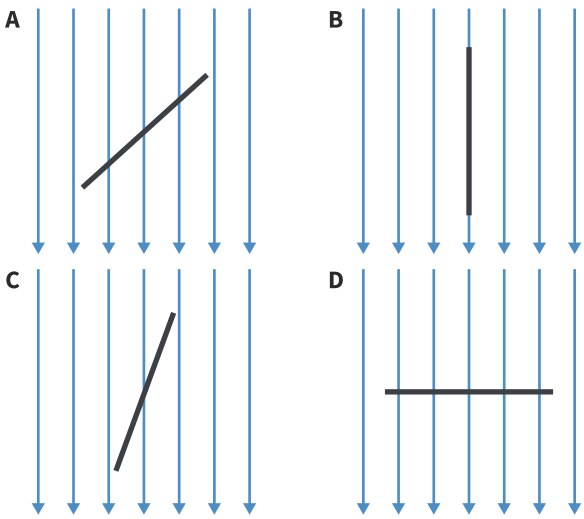
PhET 'Faraday's Law' simulation
https://phet.colorado.edu/en/simulation/faradays-law

7A Questions

THEORY REVIEW QUESTIONS

Question 1

The diagram shows the side-view of a loop of wire at different angles within a magnetic field. Rank the diagrams in order of **increasing** magnetic flux (from least flux to most flux) passing through the loop.



Question 2

An EMF can be induced in a loop when

A magnetic field strength is increasing.

B magnetic flux is decreasing.

C the area of loop perpendicular to a magnetic field is changed.

D All of the above

Question 3

A coil moves at a constant speed into a uniform magnetic field. Its area is perpendicular to the magnetic field lines. For each part of the question, select which options (A-D) apply.

a Which changes will increase the maximum magnetic flux through the coil?

b Which changes will increase the maximum magnitude of the EMF induced in the coil?

A Increasing the number of turns in the coil.

B Increasing the area of the coil.

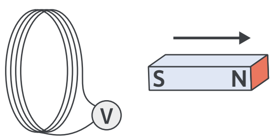
C Increasing the speed of the coil.

D Increasing the magnetic field strength.

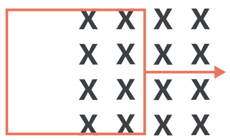
Question 4

Four scenarios in which a magnet or loop of wire is moving are shown. Which row in the table correctly shows how magnetic flux is changing for each scenario?

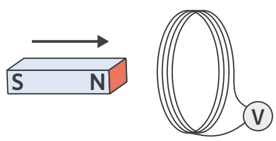
Scenario 1



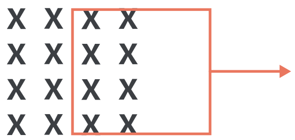
Scenario 2



Scenario 3

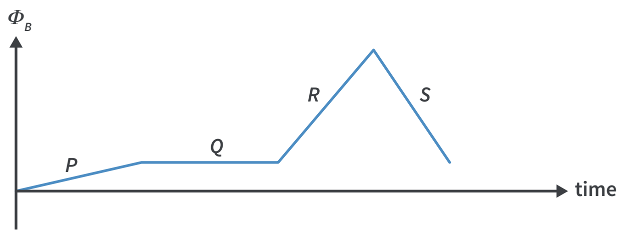


Scenario 4



	Change in magnetic flux			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
A	Decreasing	Increasing	Increasing	Decreasing
B	Decreasing	Decreasing	Increasing	Decreasing
C	Decreasing	Increasing	Decreasing	Increasing
D	Increasing	Increasing	Increasing	Decreasing

Use the following graph to answer Questions 5 and 6.



Question 5

The corresponding section of the EMF vs. time graph for section P is **negative**. For the three subsequent sections (Q–S) of the Φ_B vs time graph, decide whether the corresponding section of the EMF vs. time graph should be positive, negative, or zero.

Question 6

Which of the following options correctly compares the magnitude of the EMF corresponding to sections P and R?

A The magnitude of the EMF is greater for section P than section R.

B The magnitude of the EMF is the same for sections P and R.

C The magnitude of the EMF is greater for section R than section P.

D We need to know the strength of the magnetic field to be able to answer the question.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (4 MARKS)

A square loop of wire made out of 20 turns has side lengths of 10 cm and passes into a uniform magnetic field of strength 0.15 T. The loop takes 0.25 seconds to move from completely outside the magnetic field to fully inside the magnetic field.

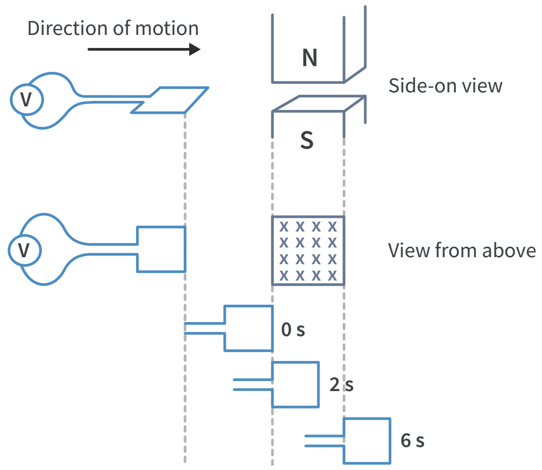
a What is the magnetic flux passing through the loop before it enters the uniform magnetic field? (1 MARK)

b What is the magnetic flux passing through the loop once it is fully inside the magnetic field? (1 MARKS)

c Calculate the magnitude of the average EMF induced in the loop as it moves from completely outside the magnetic field to completely inside. (2 MARKS)

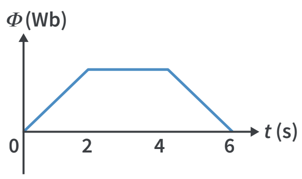
Question 8 (4 MARKS)

A square loop of 15 turns starts in a region with no magnetic field and then passes at a constant speed into, through, and out of a uniform magnetic field as indicated by the diagram. The region of the magnetic field is large enough to fit the entire loop within it. The magnetic field strength is 0.040 T and the loop has an area of 2.5×10^3 cm^2. The diagram is not drawn to scale.

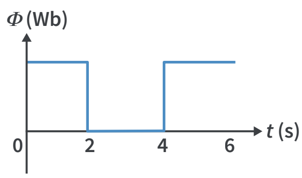


a Select which magnetic flux-time graph best represents the variation of the magnetic flux through the loop in this situation. (1 MARK)

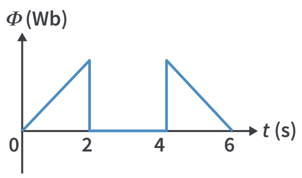
A



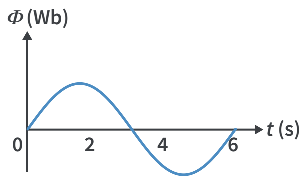
B



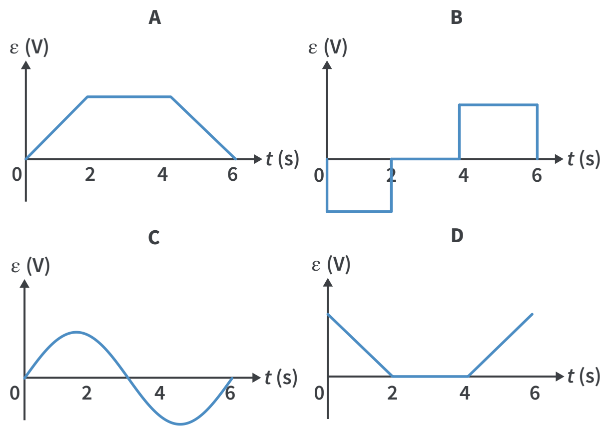
C



D



b Select which EMF-time graph best represents the variation of the EMF in the loop in this situation. (1 MARK)

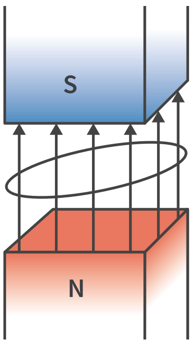


c Determine the magnitude of the average EMF induced in the loop while it is moving into the magnetic field (between $t = 0$ s and $t = 2$ s). (2 MARKS)

Adapted from 2017 VCAA Exam Section A Q6

Question 9 (1 MARK)

A circular loop of wire is being held inside a uniform magnetic field. The magnetic field lines point vertically upwards.



Which of the following actions will cause an EMF to be induced in the loop? Select all that apply.

A Moving the loop vertically upwards.

B Moving the loop vertically downwards.

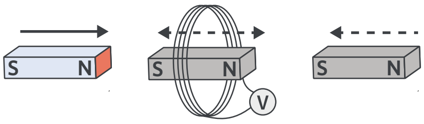
C Moving the loop horizontally outside of the magnetic field.

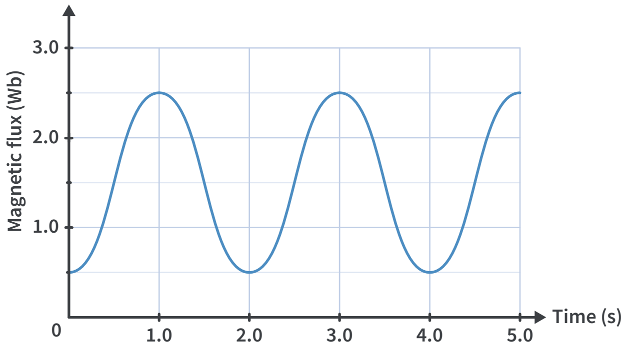
D Rotating the loop 90° about a horizontal axis.

Adapted from 2014 VCAA Physics Exam Section A Q13

Question 10 (6 MARKS)

A bar magnet oscillates through a metallic coil with 4 turns. The graph shows the magnetic flux through the loop as the magnet oscillates.





a Identify at which times on the graph the EMF induced in the loop is zero. (2 MARKS)

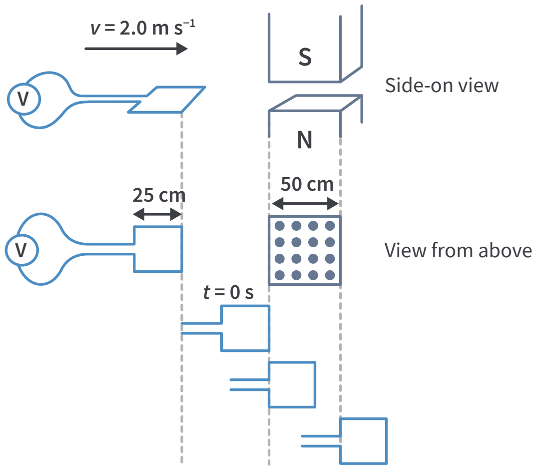
b Calculate the magnitude of the average EMF in the loop between 1.0 and 2.0 s. (2 MARKS)

c Determine at which times on the graph the magnet is in the middle of the loop. (2 MARKS)

Adapted from 2013 VCAA Exam Section A Q17

Question 11 (7 MARKS)

A square coil with 6 turns starts in a region with no magnetic field and then passes at a constant speed of $2.0\ \text{m s}^{-1}$ into, through, and out of a uniform magnetic field ($B = 3.0 \times 10^{-2}$ T) between the poles of two bar magnets as indicated by the diagram. Assume that the uniform magnetic field is a square shape with side-length of 50 cm, and the loop has a side-length of 25 cm.



a On a set of axes similar to those provided, sketch a graph of the magnetic flux through the coil against time. Assume $t = 0$ s when the front edge of the coil is just about to enter the magnetic field. Appropriate values should be included on the graph. (4 MARKS)

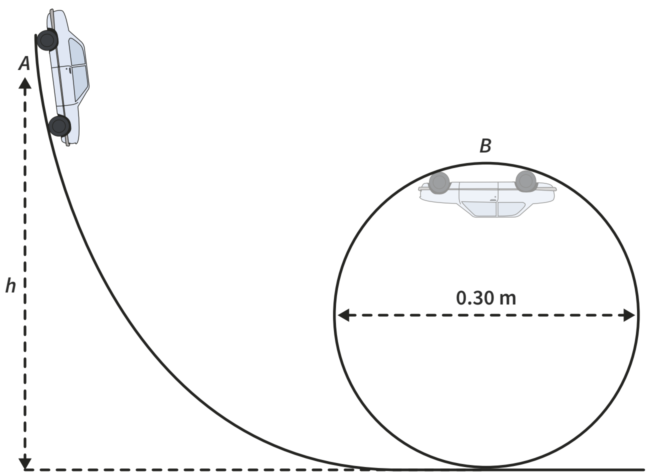
b On a set of axes similar to those provided, sketch a graph of the EMF in the coil against time. Appropriate values should be included on the graph. (3 MARKS)

Adapted from 2015 VCAA Exam Section A Q13

Previous lessons

Question 12 (6 MARKS)

An excited toddler releases her 400 g model Mercedes from rest at point *A* on top of a ramp that she got for her birthday. The model Mercedes travels down the frictionless ramp with no air resistance before entering a wicked loop with a diameter of 0.30 m. When the model Mercedes reaches point *B* it is moving with a speed of 4.0 m s^{-1}.



a Calculate the height, *h*, from which the car was released. (3 MARKS)

b Calculate the magnitude of the normal force experienced by the Mercedes when it is at point *B*. (3 MARKS)

Adapted from 2019 VCAA Exam Section B Q8

Question 13 (3 MARKS)

Determine the magnitude and direction of the electric force experienced by a proton when it is 2.00 mm to the right of a + 3.50 × 10^{-10} C point charge. Take the charge on a proton to be + 1.6 × 10^{-19} C, the mass of a proton to be 1.67 × 10^{-27} kg, and Coulomb's constant to be 8.99 × 10^{9} N m^{2} C^{-2}.

Key science skills

Question 14 (7 MARKS)

A physics class is investigating the effect of the rate of change of magnetic flux on the magnitude of the induced EMF in a coil. They use an electromagnet to vary the magnetic flux passing through a coil of wire at a constant rate. They record the magnetic flux at various times as shown in the table.

t (s)	Φ (Wb)
0	0
0.6	0.30
1.0	0.61
1.4	0.90
2.0	1.15
2.5	1.50
3.0	1.80

While varying the magnetic flux, the class measures the EMF produced in the coil to have a constant magnitude of 6 V.

a Produce a graph of the data collected by the class with flux on the vertical axis and time on the horizontal axis. Label the axes, use an appropriate scale, and include a line of best fit. (4 MARKS)

b Use the gradient of the line of best fit to approximate the number of turns in the coil. Your answer should be a whole number. (3 MARKS)

7B DIRECTION OF INDUCED CURRENT AND LENZ'S LAW

In lesson 7A we learned that a changing magnetic flux through a conducting loop can generate an EMF. But you might wonder, 'how do we know the direction of that EMF and the resulting current?' The Russian physicist Emil Lenz wondered the same thing and he developed a law to describe it. This lesson will expand on the idea of EMF generation to look at how the direction of induced current can be determined by the application of Lenz's law.

7A EMF and Faraday's law	7B Direction of induced current and Lenz's law	7C Generators and alternators

Study design key knowledge dot point

- investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced emf in a coil

Key knowledge units

Lenz's law	3.2.2.2

No previous or new formulas for this lesson

Definitions for this lesson

induced current the current produced in a conductor due to a changing magnetic field

Lenz's law 3.2.2.2

OVERVIEW

Lenz's law states that when a conductor experiences a change in magnetic flux, a current will be induced such that its magnetic field acts to oppose the initial change in magnetic flux. The direction of the induced current in a coil can then be determined by applying the right-hand coil rule in accordance with Lenz's law.

THEORY DETAILS

In lesson 7A we learned that a change in magnetic flux through a conducting loop induces an EMF (or voltage). In accordance with Ohm's law $\left(I = \frac{V}{R}\right)$, which will be revised in lesson 8A, this EMF is associated with an induced current. In lesson 6B we learned that when an electrical current passes through a loop, it will generate its own magnetic field with a direction that can be determined by the right-hand coil rule. Lenz's law combines these two ideas to determine the direction of the induced current.

In order to determine the direction that this induced current will flow around a loop, we first need to identify:

- the **direction** that flux is passing through the loop (upwards, downwards, left, right, etc.).
- whether the flux is **increasing** or **decreasing**.

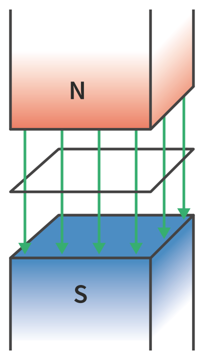


Figure 1 The direction of the magnetic flux through the loop is down the page.

The direction that magnetic flux passes through a loop of wire is the same as the direction of the magnetic field lines passing through it (which travel from the north to the south poles of magnets). For example, the magnetic flux through the loop of wire in Figure 1 is directed downwards.

To identify whether the flux through a loop is increasing or decreasing, determine whether:

- the area of the loop within the magnetic field is increasing or decreasing; or
- the strength of the magnetic field within the loop is increasing or decreasing.

Consider Figure 2, which depicts a loop of wire moving through a static, uniform magnetic field that is directed into the page when viewed from above:

- From position *W* to position *X*, the area of the loop within the magnetic field increases. Hence, **the flux through the loop (into the page when viewed from above) increases**.
- From position *X* to position *Y*, the entire loop stays within the magnetic field. Hence, there is **no change in magnetic flux** through the loop.
- From position *Y* to position *Z*, the area of the loop within the magnetic field decreases. Hence, **the flux through the loop (into the page) decreases**.

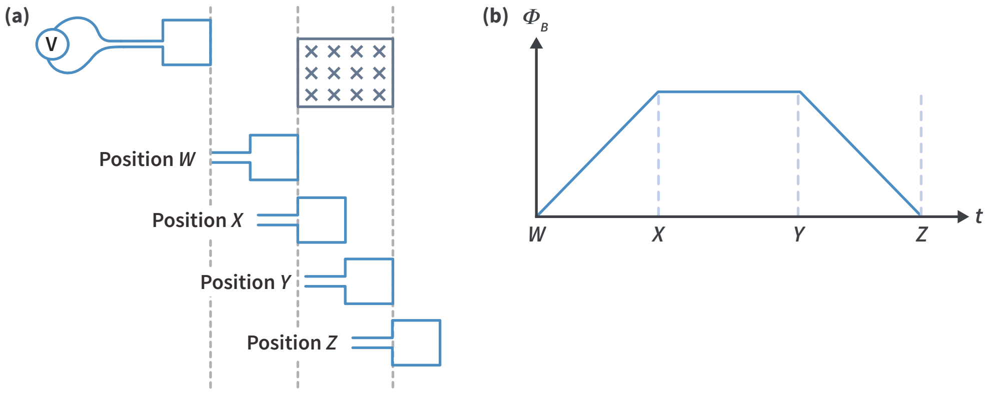


Figure 2 (a) A loop of wire moving into, through, and then out of a magnetic field. **(b)** The magnetic flux graph for the loop of wire.

Lenz's law states that:

> *an induced current will flow in a direction such that the **magnetic field created by the current** will **oppose** the **change in flux** that induced the current.*

Problem solving process

To determine the direction of an induced current:

1 Identify whether the magnetic flux is **increasing or decreasing**.

2 Identify the **direction of the original magnetic field** ('up', 'right', 'into the page' etc.).

3 Identify the **direction of the induced magnetic field**:

- If the flux is **increasing** (found in step 1) then the magnetic field is in the **opposite direction** to the original field (found in step 2).
- If the flux is **decreasing** (found in step 1) then the magnetic field is in the **same direction** as the original field (found in step 2).

4 Apply the right-hand coil rule, with thumb pointing in the direction of the induced magnetic field identified in step 3, to determine the **direction of the induced current**.

Consider the loop in Figure 2 as it moves from position *W* to position *X*:

1. The magnetic flux **increases** since the area within the field increases.
2. The original magnetic field is **into the page**.
3. The magnetic field created by the induced current will be in the opposite direction to the original magnetic field (since the flux is increasing) to oppose the change in flux: **out of the page**.
4. Using the right-hand coil rule, with the thumb pointing out of the page, the induced current flows in an **anticlockwise** direction when viewed from above.

Now consider the loop in Figure 2 as it moves from position *Y* to position *Z*:

1. The magnetic flux **decreases** since the area within the field decreases.
2. The original magnetic field is **into the page**.
3. The magnetic field created by the induced current will be in the same direction as the original magnetic field (since the flux is decreasing) to oppose the change in flux: **into the page**.
4. Using the right-hand coil rule, with the thumb pointing into the page, the induced current flows in a **clockwise** direction when viewed from above.

Note that we can reach the same results predicted by Lenz's law if we apply the right-hand palm rule to the positive charges in a conducting loop as it moves through a magnetic field.

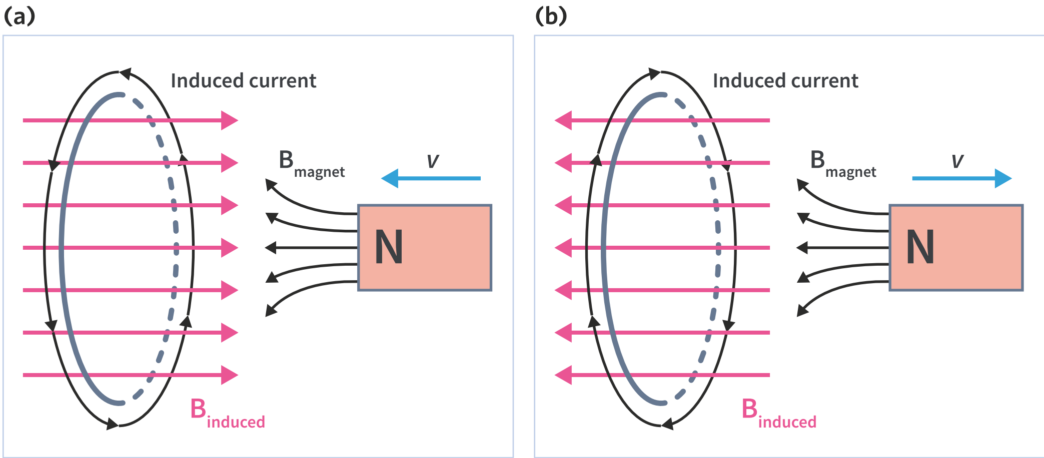


Figure 3 The induced magnetic field and induced current when the north pole of a magnet is moving **(a)** towards and **(b)** away from a loop of wire.

Figure 3 depicts current being induced in a conducting loop due to a changing magnetic field strength through the loop, rather than a changing area within the magnetic field. The process for determining the direction of the induced current is the same.

In Figure 3(a):

1. The magnetic flux through the loop is **increasing** as the magnet approaches the loop (increasing magnetic field strength).
2. The original magnetic field is to the **left** (in the direction of the magnetic field lines).
3. The induced magnetic field will be in the opposite direction to the original magnetic field (since the flux is increasing) to oppose the change in flux: to the **right**.
4. Using the right-hand coil rule, with the thumb pointing to the right, the induced current when viewed from the magnet is **anticlockwise**.

In Figure 3(b):

1. The magnetic flux through the loop is **decreasing** as the magnet moves away from the loop (decreasing magnetic field strength).
2. The original magnetic field is to the **left** (in the direction of the magnetic field lines).
3. The induced magnetic field will be in the same direction as the original magnetic field (since the flux is decreasing) to oppose the change in flux: to the **left**.
4. Using the right-hand coil rule, with the thumb pointing to the left, the induced current when viewed from the magnet is **clockwise**.

In a VCE Physics exam, it is common to need to explain how we determined the direction of current (that is, how we applied Lenz's law) rather than providing the end result only. In these cases, we need to explicitly describe the steps from the previous 'problem solving process'. The following provides a template for answering such questions:

- The magnetic flux through the loop is [**increasing/decreasing** (step 1)][**direction** (step 2)].
- By Lenz's law, the induced magnetic field will oppose this change in flux, so it will be directed [**direction** (step 3)].
- Using the right-hand coil rule, the induced current will flow [**direction** (step 4)].

Theory summary

- Lenz's law states that the induced current will flow in a direction such that the magnetic field it creates will oppose the **change** in flux that generated the current.
  - If magnetic flux through a loop is **increasing**, the induced magnetic field will be in the **opposite direction to the original magnetic field**.
  - If magnetic flux through a loop is **decreasing**, the induced magnetic field will be in the **same direction as the original magnetic field**.
  - The right-hand coil rule is used to determine the direction of the induced current once the direction of the induced magnetic field has been identified.

KEEN TO INVESTIGATE?

Molecular Expresions 'Lenz's Law' simulation
https://micro.magnet.fsu.edu/electromag/java/lenzlaw/

PhET 'Faraday's Law' simulation
https://phet.colorado.edu/en/simulation/faradays-law

YouTube video: Lenz's Law Demonstration – Penn Physics
https://youtu.be/k2RzSs4_Ur0

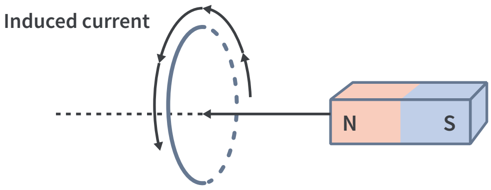
YouTube video: World's First Electric Generator – Veritasium
https://youtu.be/NqdOyxJZj0U

7B Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1 and 2.

A bar magnet is moved towards a loop of wire with the north pole facing the loop, which induces an **anticlockwise** current when viewed from the magnet. This is shown in the diagram.



Question 1

By applying Lenz's law, we can say that the induced current is anticlockwise because the magnetic field it produces

A opposes the magnetic field of the magnet.

B opposes the current of the magnet.

C opposes the change in magnetic flux through the loop.

D opposes the magnetic field of the Earth.

Question 2

If the magnet moves away from the loop (to the right), in what direction will the induced current flow around the loop?

A There will be zero induced current.

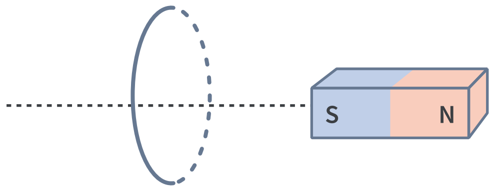
B It will flow in a clockwise direction when viewed from the right.

C It will flow in an anticlockwise direction when viewed from the right.

D There is not enough information to know.

Use the following information to answer Questions 3 and 4.

A bar magnet is positioned near a loop of wire with the south pole facing the loop, as shown.



Question 3

If the magnet moves towards the loop (to the left), in what direction will the induced current flow around the loop?

A There will be zero induced current.

B It will flow in a clockwise direction when viewed from the right.

C It will flow in an anticlockwise direction when viewed from the right.

D There is not enough information to know.

Question 4

If the magnet moves away from the loop (to the right), in what direction will the induced current flow around the loop?

A There will be zero induced current.

B It will flow in a clockwise direction when viewed from the right.

C It will flow in an anticlockwise direction when viewed from the right.

D There is not enough information to know.

Question 5

Lenz's law states that the direction of the current induced in a coil will

A directly oppose the change in magnetic flux through the coil.

B create a magnetic field such that the flux produced will oppose the original magnetic flux through the coil.

C directly oppose the original magnetic flux through the coil.

D create a magnetic field such that the flux produced will oppose the change in magnetic flux through the coil.

Question 6

If the change in the magnetic flux through a loop of wire is increasing downwards at a constant rate, then the induced current will result in a magnetic field that is

A acting upwards with constant strength.

B acting downwards with constant strength.

C acting upwards with increasing strength.

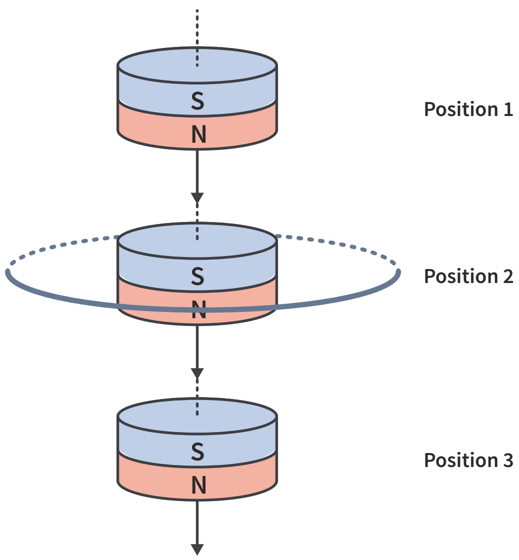
D acting downwards with increasing strength.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (5 MARKS)

Whilst playing with a toy magnet, a baby accidentally drops it through a coil of wire. The magnet falls north side down and passes through the centre of the coil, as shown in the diagram.

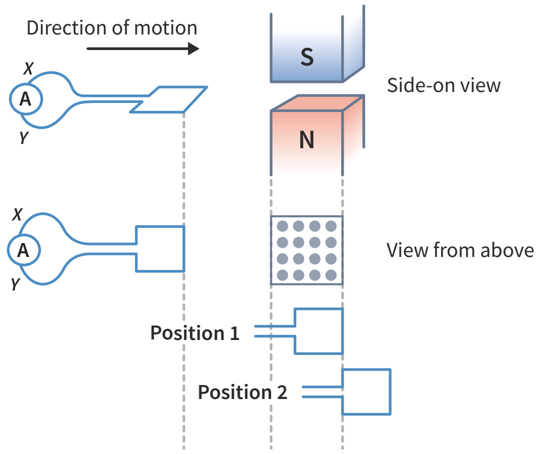


a As viewed from above, determine the direction of the current induced in the coil as the magnet falls from position 1 towards position 2. Justify your answer. (3 MARKS)

b As viewed from above, determine the direction of the current induced in the coil as the magnet falls from position 2 towards position 3. If this is a different direction to part **a**, what has caused this difference? (2 MARKS)

Question 8 (3 MARKS)

A square loop of wire is moving at a constant speed and passes into and then out of a uniform magnetic field as shown in the diagram.

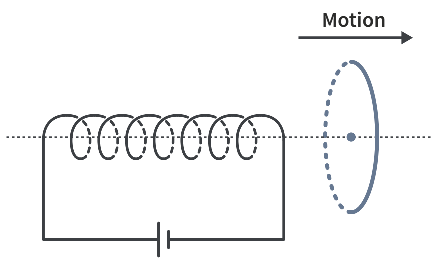


Determine the direction of the induced current through the ammeter (*X* to *Y*, or *Y* to *X*) in the loop as it **exits** the magnetic field (moves from position 1 to position 2). Justify your answer.

Adapted from 2018 NHT VCAA Exam Section B Q4

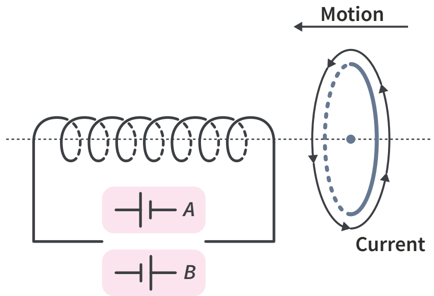
Question 9 (6 MARKS)

Attempting to understand the brilliance of wireless power, Sebastian is experimenting with a loop of wire and a solenoid. For his first experiment, shown in the diagram, Sebastian moves the loop away from the solenoid (to the right) and measures the direction of the induced current.



a Determine the direction of the induced current (clockwise or anticlockwise) in the loop of wire, as viewed from the solenoid. Explain your answer. (4 MARKS)

b After replacing the solenoid's cell, Sebastian has forgotten which side of the cell is positive and which is negative. Sebastian moves the loop of wire towards the solenoid and measures an anticlockwise current, as viewed from the solenoid. This is shown in the diagram.

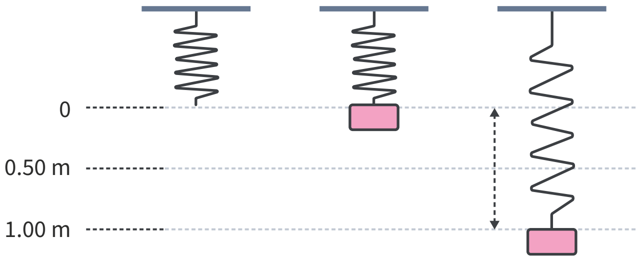


Determine the direction current will flow in the solenoid circuit and, hence, in which orientation (*A* or *B*) the cell has been connected. (2 MARKS)

Previous lessons

Question 10 (7 MARKS)

A mass of 1.50 kg is attached to a spring which has a spring constant of 29.4 N m^{-1}. When the mass is released from the unstretched position of the spring, it falls a distance of 1.00 m where it briefly comes to rest. Consider the zero of gravitational potential energy to be at the mass' lowest point.

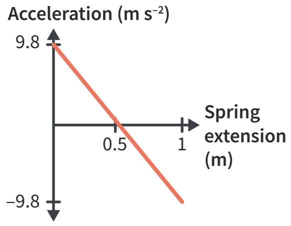


a At its lowest point, calculate the spring potential energy. (2 MARKS)

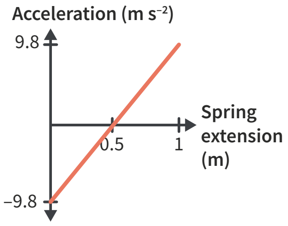
b Calculate the maximum speed of the mass after it is released from the unstretched position. (3 MARKS)

c Which one of the following graphs (**A**–**E**) best displays the acceleration of the mass as it falls from its highest point to its lowest point? Take upwards acceleration to be positive. Explain your answer. (2 MARKS)

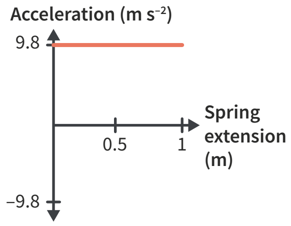
A



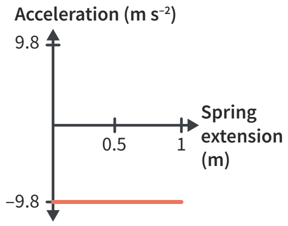
B



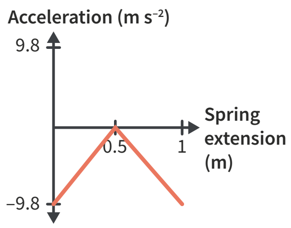
C



D



E



Adapted from 2015 VCAA Exam Section A Q6

Question 11 (5 MARKS)

Within a particle accelerator, a proton is accelerated from rest between two plates that are 7.5 cm apart and have a potential difference of 10 000 V between them.

Mass of proton	1.7×10^{-27} kg
Charge on proton	$+1.6 \times 10^{-19}$ C

a Calculate the strength of the electric field that exists between the two plates. Include an appropriate unit. (3 MARKS)

b Calculate the speed of the proton as it exits the particle accelerator. Ignore relativistic effects. (2 MARKS)

Adapted from 2018 NHT VCAA Exam Section B Q2

Key science skills

Question 12 (3 MARKS)

A student is conducting an investigation where she oscillates a magnet near a fixed loop of wire and she measures the direction of the induced current when the magnet is moving towards the loop and compares this to when it is moving away from the loop.

Identify the independent variable, dependent variable, and a controlled variable in this experiment.

7C GENERATORS AND ALTERNATORS

Generators and alternators utilise the principle of electromagnetic induction to transform kinetic energy into electricity. We will investigate the components and operation of these devices and variables which affect their electrical output.

7A EMF and Faraday's law	7B Direction of induced current and Lenz's law	7C Generators and alternators

Study design key knowledge dot points

- explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively.
- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})

Key knowledge units

Alternators	3.2.3.1
AC power quantities	3.2.4.1
DC generators	3.2.3.2

Formulas for this lesson

Previous lessons		New formulas
7A	* $\Phi_B = B_\perp A$	$f = \frac{1}{T}$
7A	* $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

AC (alternating current) electricity electricity with a periodically alternating direction of current and voltage

alternator a device that transforms kinetic energy into AC electricity by electromagnetic induction; an AC generator

amplitude the magnitude of the maximum variation of any quantity with a changing value

DC (direct current) electricity electricity with a constant direction of current and voltage

frequency the number of cycles completed per unit of time

generator a device that transforms kinetic energy into (either AC or DC) electricity by electromagnetic induction

period the time taken to complete one cycle

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation

Alternators 3.2.3.1

OVERVIEW

Alternators transform kinetic energy into AC electricity. A conducting coil rotates within a magnetic field, creating an alternating EMF. The coil is kept in constant contact with an external circuit through the use of slip rings.

THEORY DETAILS

A generator is a device that uses a rotating coil within a magnetic field to generate electricity. An alternator is a generator that has an AC output.

In lesson 7A, we learned that an EMF is induced when there is a changing magnetic flux through a coil. We also learned that one way to change the flux through a coil is to rotate it within a magnetic field, which is the basis of a generator. In this way, the kinetic energy used to rotate the coil is transformed into electricity. A generator performs the **opposite** energy transformation to a motor (from lesson 6D).

Magnetic flux and EMF graphs for alternators

Figure 1 shows the magnetic flux (blue graph) and the EMF (red graph) for a coil as it rotates at a constant speed within a static uniform magnetic field. Note that the vertical axis represents a different quantity for each graph. In the situation shown, the coil starts in an orientation which is parallel to the magnetic field. The angle of rotation for each orientation shown is measured from the starting position. There are some important features to notice about the magnetic flux-time graph:

- The flux is zero whenever the coil is parallel to the magnetic field.
- The magnitude of the flux is a maximum whenever the coil is perpendicular to the magnetic field.
- A negative flux indicates that the magnetic field lines are passing through the coil in the opposite direction, relative to the coil, to a positive flux. The choice of which direction is positive is not important, but we must be consistent.
- The flux varies sinusoidally with time.

As we learned in lesson 7A, the EMF is proportional to the negative value of the gradient of the magnetic flux-time graph. There are some important features to notice about the EMF-time graph:

- The EMF is zero whenever the magnitude of the flux is a maximum (when the coil is perpendicular to the magnetic field).
- The magnitude of the EMF is a maximum whenever the flux is zero (when the coil is parallel to the magnetic field).
- The EMF has a positive value whenever the flux is decreasing (negative gradient) and it has a negative value whenever the flux is increasing (positive gradient).
- The EMF varies sinusoidally with time. The maximum value of the EMF graph occurs one quarter of a cycle later than the maximum value of the magnetic flux.

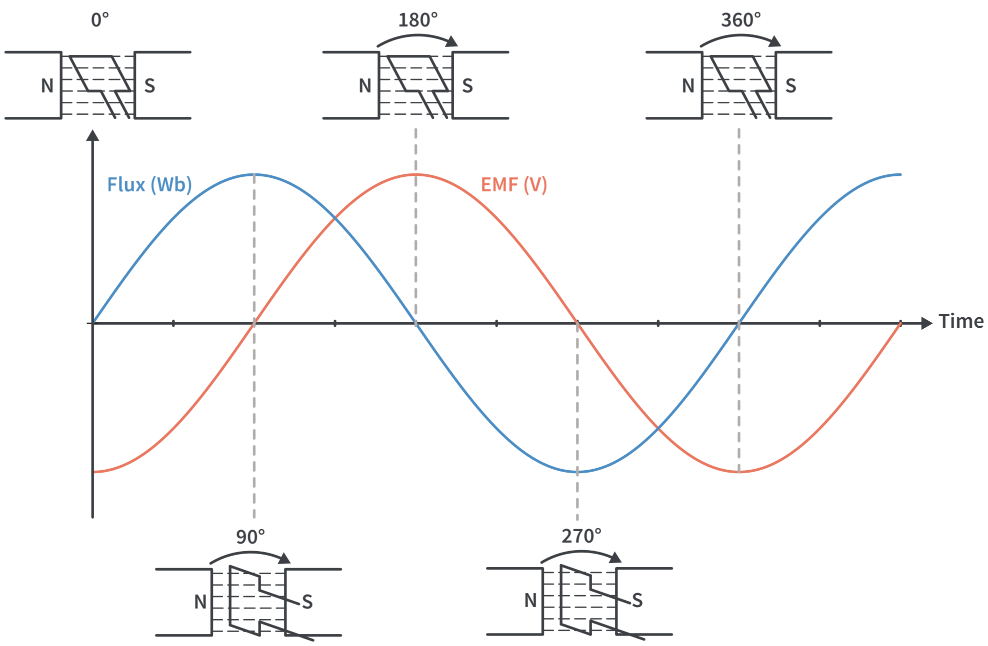


Figure 1 The magnetic flux and EMF in a coil that is rotating uniformly within a constant magnetic field. When the flux decreases, the EMF is positive. When the flux increases, the EMF is negative.

The output of an alternator is the EMF generated in the rotating coil, and hence the alternator has an AC output.

Slip rings

Slip rings are conducting rings that allow the coil in an alternator to rotate while maintaining electrical contact with a stationary external circuit. Each end of the coil slides around the surface of its ring. By maintaining contact, the alternating EMF induced in the coil is passed, unaltered, into the external circuit, resulting in an AC output.

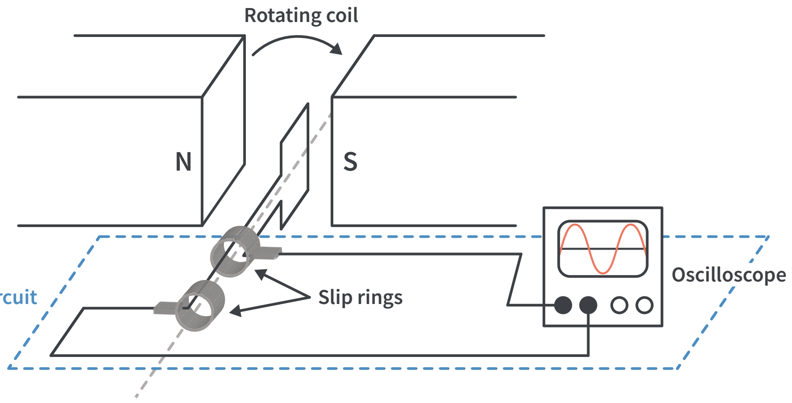


Figure 2 An alternator is connected by slip rings to an oscilloscope which records an AC output.

AC power quantities 3.2.4.1

OVERVIEW

AC voltage has the properties of amplitude, frequency, and period. These quantities can be identified from graphs of voltage against time. Each of these quantities are affected by the speed of rotation of the coil in an alternator.

THEORY DETAILS

The sinusoidal variation over time of the voltage from an alternator can be described by the maximum value of the voltage and the time it takes to complete a full cycle:

- The peak (maximum) value of an AC voltage is its amplitude.
- The time taken to complete one full cycle is its period (T). The frequency (f) describes the same information as the period in a different way. Frequency is defined as the number of full cycles that are completed per second, and it is measured in hertz (Hz).

$$f = \frac{1}{T}$$

f = frequency (Hz), T = period (s)

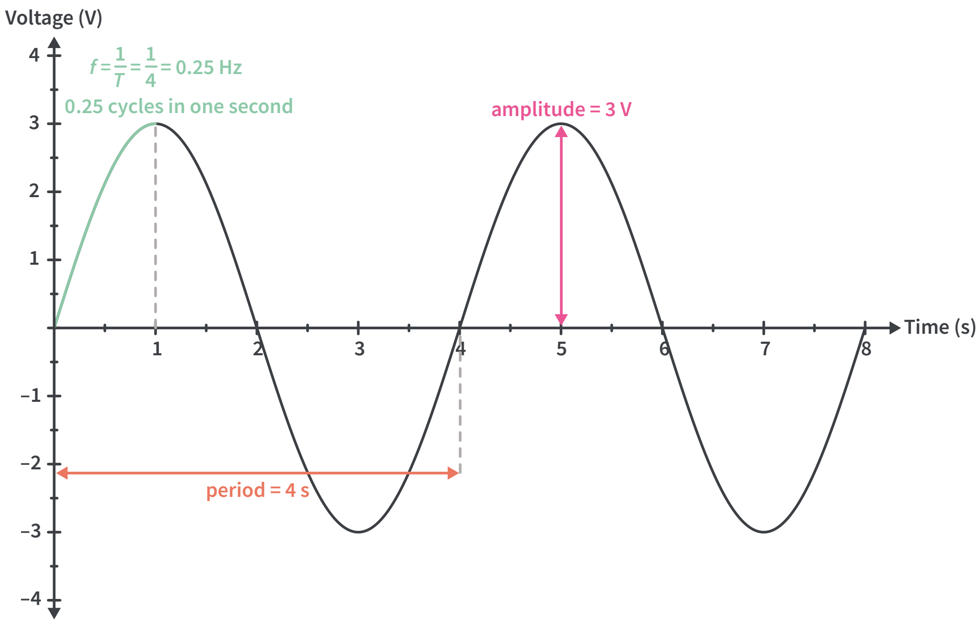


Figure 3 The frequency, period, and amplitude of an AC voltage can be found from a voltage-time graph. The frequency and period provide two ways of describing the same information.

When the speed of rotation of the coil in an alternator is increased (as shown in Figure 4), it will affect the frequency, period, and amplitude of the EMF in the following ways.

- The number of full rotations of the coil per second increases, so the **frequency increases**.
- The time taken to complete one full rotation decreases, so the **period decreases**.
- The rate of change of flux through the coil increases, so the EMF **amplitude increases** as described by $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$. The EMF amplitude is proportional to the frequency (and inversely proportional to the period).

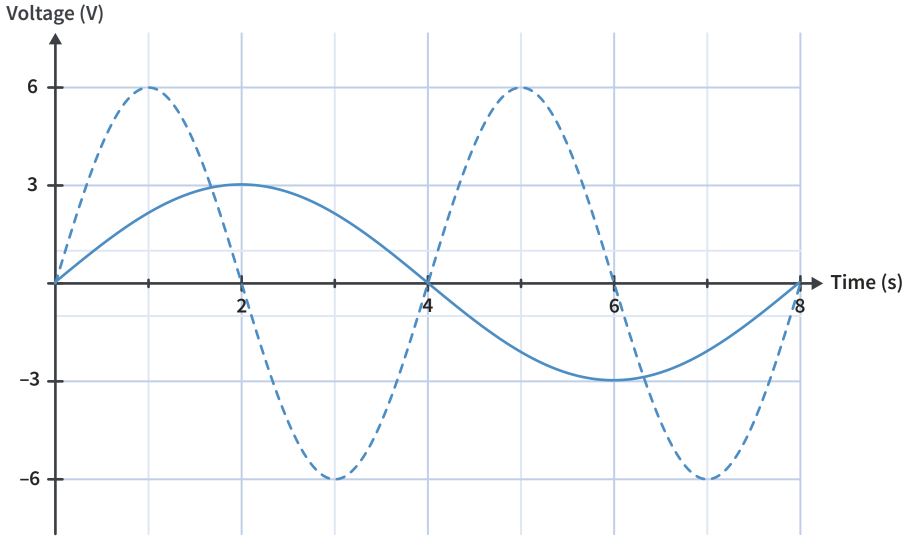


Figure 4 The voltage output for the same alternator at two different rotation speeds. When the frequency of rotation is doubled (the period is halved), the amplitude doubles.

1 **Worked example**

An alternator is being used to produce electricity. The alternator coil has five turns and an area of 0.40 m^2. The coil completes three full rotations per second inside a uniform magnetic field of strength 5.0 × 10^{-3} T.

a **Calculate the magnitude of the average EMF in the coil as it completes one quarter of a revolution from the vertical to the horizontal position.**

b **Determine the magnitude of the average EMF if the frequency is increased to nine rotations per second.**

a To calculate the magnitude of the average EMF, we need to apply Faraday's law: $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$.

In one quarter of a revolution, magnetic flux changes from a maximum ($\Phi_B = BA$) to zero:

$\Delta\Phi_B = BA - 0 = (5.0 \times 10^{-3} \times 0.40) - 0 = 2.0 \times 10^{-3}$ Wb

The time, Δt, over which this $\Delta\Phi$ occurs is one quarter of a period:

$T = \frac{1}{f} = \frac{1}{3} = 0.333$ s $\therefore \Delta t = \frac{T}{4} = \frac{0.333}{4} = 0.0833$ s

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 5 \times \frac{2.0 \times 10^{-3}}{0.0833} = 0.12$ V

b We could calculate the magnitude of the average EMF using the same process as in part **a**, using a different frequency ($f = 9$ Hz).

Alternatively, we can recognise that the frequency has tripled so the magnitude of the EMF must also triple.

$\varepsilon = 3 \times 0.12 = 0.36$ V

DC generators 3.2.3.2

OVERVIEW

DC generators (also known as 'dynamos') operate on a similar principle as alternators, however the output voltage has a constant direction due to the use of a split ring commutator.

THEORY DETAILS

While an alternator relies on slip rings to maintain a constant connection between the coil and the external circuit, which results in an AC output, **a DC generator uses a split ring commutator** to switch the connection between the coil and the external circuit every half rotation. This 'rectifies' the sinusoidal EMF, which means that the output voltage has a constant direction. It is important to understand that the output voltage does change over time, but it always has the same sign, as shown in Figure 5 and Figure 6.

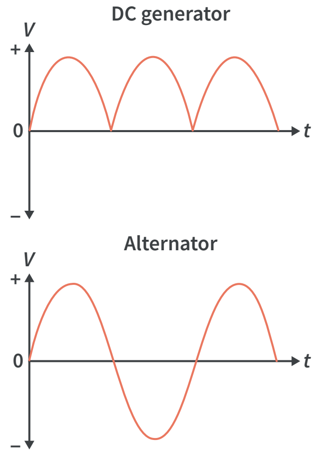


Figure 6 A comparison of the voltage output for a DC generator and an alternator

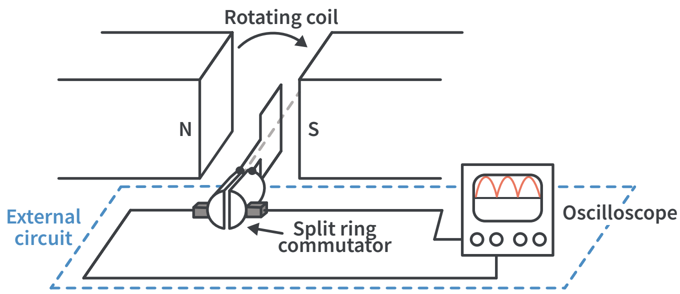


Figure 5 A DC generator is connected via a split ring commutator to an oscilloscope which records the induced EMF that has a constant direction.

The apparatus of an alternator is similar to a DC generator, which is also similar to a DC motor, however their functions are different. Table 1 summarises the similarities and differences between the three. Note that AC motors are not part of the VCE Physics course.

Table 1 The similarities and differences between alternators, DC generators, and DC motors

	Energy transformation	Connection between coil and external circuit	Input	Output
Alternator	KE → Electrical	Slip rings	Rotation of coil in one direction	AC electricity
DC generator	KE → Electrical	Split ring commutator	Rotation of coil in one direction	DC electricity (rectified sinusoid)
DC motor	Electrical → KE	Split ring commutator	DC electricity	Rotation of coil in one direction

Theory summary

- Alternators convert kinetic energy to AC electricity.
  - The changing magnetic flux within the coil induces an oscillating EMF.
  - Slip rings maintain a constant electrical connection between the coil and the external circuit, resulting in an AC output.
- The AC voltage produced by an alternator can be characterised in terms of its:
  - amplitude – the magnitude of the output voltage.
  - frequency (f) – the number of rotations of the coil completed per second.
  - period (T) – the time for the coil to complete one full rotation.
- The amplitude of the EMF varies in proportion to the frequency.
- DC generators also convert kinetic energy to DC electricity.
  - The only difference in the apparatus between DC generators and alternators is that a split ring commutator is used in DC generators whereas slip rings are used in alternators.
  - The only difference between the function of a DC generator and an alternator is that a DC generator produces a voltage output in a constant direction (a rectified sinusoid) whereas an alternator produces an AC output.
  - The output from the DC generator still varies, but only in one direction.

KEEN TO INVESTIGATE?

Fendt 'Generator' simulation
https://www.walter-fendt.de/html5/phen/generator_en.htm

YouTube video: Creative Learning – AC generator
https://youtu.be/gQyamjPrw-U

YouTube video: EdisonTechCenter – Simple explanation of a generator
https://youtu.be/UL_ryxub-RA

7C Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following statements about AC alternators and DC generators is correct?

A Alternators and generators convert electricity into kinetic energy.

B Alternators convert kinetic energy into electricity and generators convert electricity into kinetic energy.

C Alternators convert electricity into kinetic energy and generators convert kinetic energy into electricity.

D Alternators and generators convert kinetic energy to electricity.

Question 2

The two diagrams show the coil of an alternator at two different orientations during its uniform rotation.
In orientation *X*, the coil is parallel to the magnetic field. In orientation *Y*, the coil is perpendicular to the magnetic field.

Choose which orientation corresponds to

a the maximum magnitude of magnetic flux through the coil.

b zero flux through the coil.

c the maximum magnitude of EMF in the coil.

d zero EMF in the coil.

Question 3

What is the relationship between the frequency of rotation of an alternator or generator coil and the frequency of the EMF induced in the coil?

A EMF frequency is equal to twice the rotation frequency.

B EMF frequency is equal to the rotation frequency.

C EMF frequency is equal to half the rotation frequency.

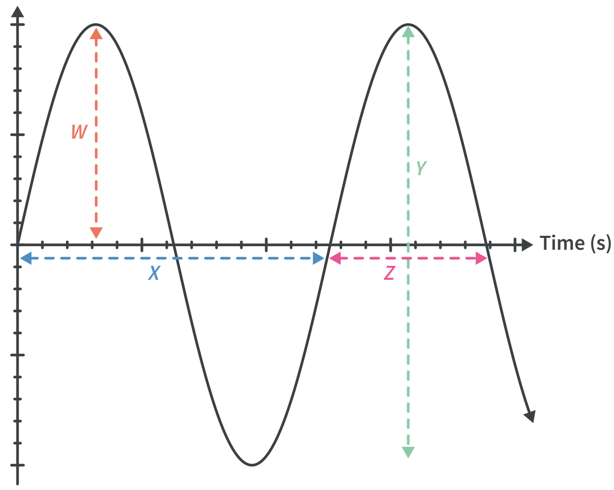
D EMF frequency depends on the number of turns in the coil.

Question 4

For the AC voltage-time graph shown, determine which measurement (*W*-*Z*) represents

a the period.

b the amplitude.



Question 5

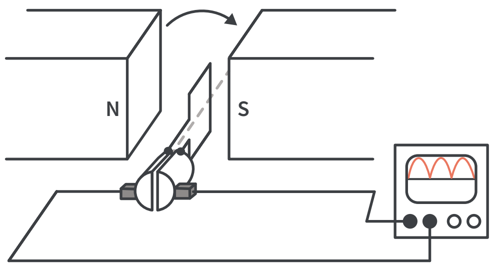
Which option correctly describes the effect of an increase in alternator coil rotation speed on the frequency, period and amplitude of the AC voltage output?

	Frequency	Period	Amplitude
A	Increase	Decrease	Increase
B	Increase	Increase	Decrease
C	Decrease	Increase	Decrease
D	Decrease	Decrease	Increase

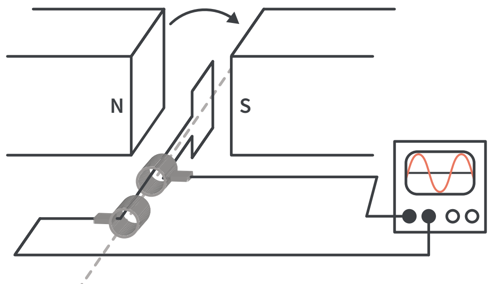
Question 6

A teacher provides a student with the two apparatuses pictured.

A



B



Determine which apparatus (**A** or **B**) corresponds to or uses each of the following:

AC alternator	
DC generator	
Slip rings	
Split ring commutator	
DC output	
AC output	

EXAM-STYLE QUESTIONS

This lesson

Question 7 (8 MARKS)

Swathi and Javier are investigating the operation of a simple alternator. They rotate the coil at a constant speed within a uniform horizontal magnetic field so that each complete turn takes 20 ms.

a Calculate the frequency of AC power that the alternator will output. (2 MARKS)

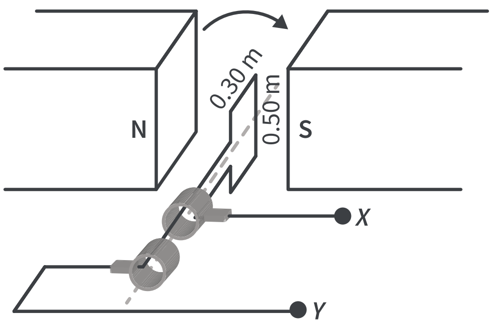
b Describe the orientation of the alternator coil when the EMF output has a maximum magnitude. Justify your answer. (2 MARKS)

c Javier is unhappy with the voltage output of the alternator, so Swathi suggests some changes that she believes will increase the amplitude of the EMF output. Copy and complete the table provided to indicate whether each of Swathi's suggestions will increase, decrease, or have no effect on the maximum EMF magnitude of the alternator. (4 MARKS)

Suggested change	Effect on EMF amplitude (increase, decrease, no effect)
Decrease the period of rotation of the coil.	
Decrease the strength of the permanent magnets.	
Increase the number of turns in the coil.	
Increase the area of the coil.	

Question 8 (10 MARKS)

An alternator is constructed using a rectangular coil of 20 turns with dimensions 0.30 m × 0.50 m. The coil rotates at a constant speed within a uniform magnetic field such that it completes one full rotation every 0.50 s. The magnetic field strength is 0.090 T.



a The rectangular loop is rotated clockwise from the vertical position shown. On a single set of axes like the ones provided, draw a graph of the variation in magnetic flux versus time **and** a graph of the variation in EMF versus time for **two full rotations**. Clearly label each of the graphs and include a scale on the time axis. No calculations should be completed for your answer. (3 MARKS)

b Calculate the magnitude of magnetic flux passing through one turn when it is in the vertical position shown. (2 MARKS)

c Calculate the frequency of the EMF output. (1 MARKS)

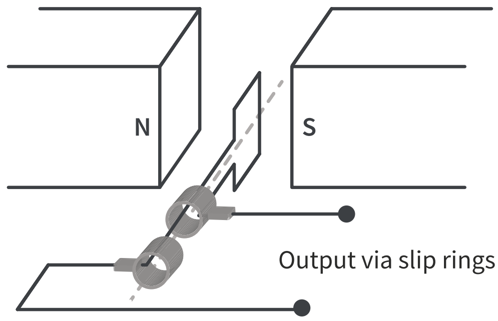
d Determine the magnitude of the average EMF induced in the coil as it completes one quarter of a revolution, from the vertical position to the horizontal position. (2 MARKS)

e Explain the function of slip rings with reference to the output of an alternator. (2 MARKS)

Adapted from 2012 VCE Physics Exam 2 Section A AoS 1 Q7

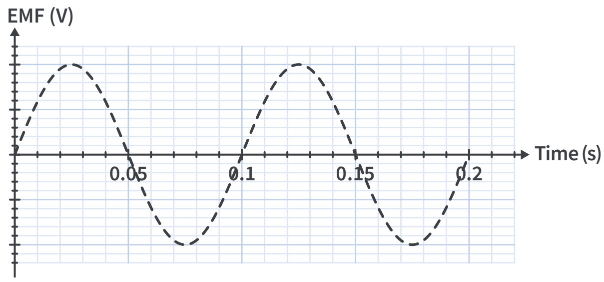
Question 9 (5 MARKS)

An alternator is constructed that consists of a square coil of five turns and that completes 10 full cycles per second. The loop is entirely within an external magnetic field of strength 8.0×10^{-3} T.



a The magnitude of the average EMF induced in the coil as it completes one quarter turn, from a vertical position to a horizontal position, is 1.6 V. Determine the side length of the square coil in centimetres. (4 MARKS)

b The EMF-time graph below shows the output of the alternator for two complete rotations.

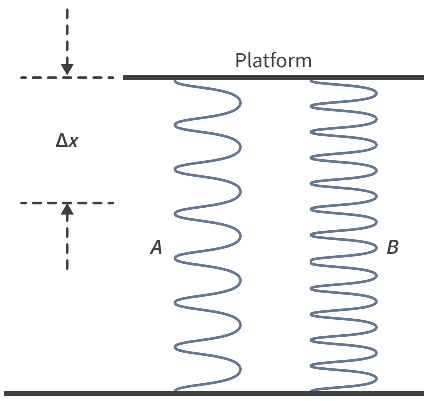


Copy the axes of the EMF versus time graph, and use a solid line to sketch the voltage output for two complete rotations if the slip rings were replaced with a split ring commutator. (1 MARK)

Previous lesson

Question 10 (8 MARKS)

Students are investigating a spring system consisting of two different springs, *A* and *B,* in parallel. The two springs have the same unstretched length, however spring *B* has a larger spring constant than spring *A*. A platform rests horizontally on both of the springs. Assume that the platform has negligible mass.



Spring *A* has a spring constant, k_A, of 3.00 N m^{-1}.

The students place various masses on the platform and record the compression in the vertical direction, Δx.

The measurements are shown in the following table.

Mass (g)	Vertical compression, Δx (cm)
0	0
20.0	1.96
40.0	3.92
60.0	5.88
80.0	7.83

a When the 60.0 g mass rests on the platform, calculate the upward force exerted on the platform by spring *A.* (2 MARKS)

b When the 60.0 g mass rests on the platform, calculate the upward force exerted on the platform by spring *B.* (2 MARKS)

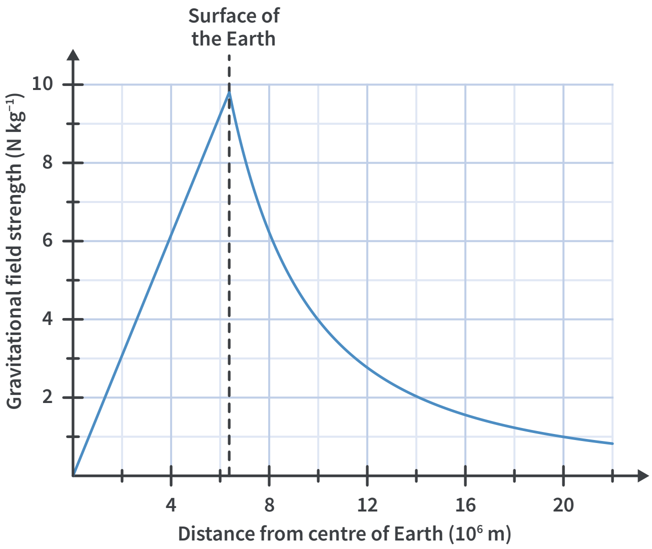
c Determine the spring constant for spring *B*, k_B. (2 MARKS)

d Calculate the work done to compress spring *B* by 5.00 cm. (2 MARKS)

Adapted from 2019 VCAA Exam Section B Q19

Question 11 (5 MARKS)

Elon Musk launched his own car, a Tesla Roadster, from the surface of the Earth into space. Assume the car has a mass of 1300 kg and that it travelled to a distance of 20×10^6 m from the centre of the Earth.



a What is the increase in gravitational potential energy of Elon Musk's car on this journey? (3 MARKS)

b Calculate the decrease in gravitational potential energy for the car if Elon Musk were somehow able to drive it from the surface to the centre of the Earth. Assume Earth is a sphere with a uniform density and a radius of $R_E = 6.37 \times 10^6$ m. (2 MARKS)

Adapted from 2019 VCAA Exam Section B Q4

Key science skills

Question 12 (9 MARKS)

Students measure the voltage output, at 0.5 second intervals, when a coil rotates uniformly inside a constant magnetic field. The voltage measurements have an uncertainty of ±0.5 V. Assume the uncertainty in measured time is negligible.

Time (s)	Voltage output (V)
0.0	7.6
0.5	5.3
1.0	0.2
1.5	5.8
2.0	7.7
2.5	6.0
3.0	0.3
3.5	5.7
4.0	8.1
4.5	5.7
5.0	0.1
5.5	5.9
6.0	8.0

a Plot the data for the voltage output (on the vertical axis) against time (on the horizontal axis). Include axis labels with units, an appropriate scale, uncertainty bars, and an appropriate curve of best fit. (5 MARKS)

b Determine the frequency of rotation of the coil. (2 MARKS)

c Identify whether the coil was connected to the external circuit via slip rings or a split ring commutator. Explain your answer. (2 MARKS)

CHAPTER 7 QUESTIONS

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

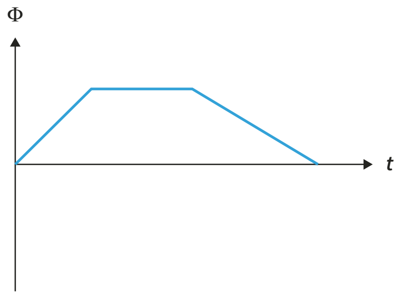
SECTION A

All questions in this section are worth one mark.

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

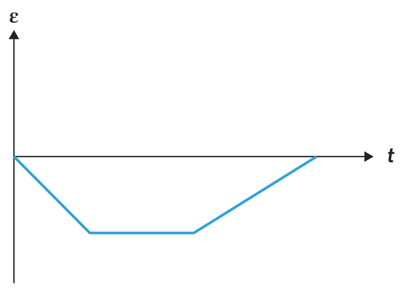
Question 1

The graph shows the magnetic flux through a coil of wire over time.

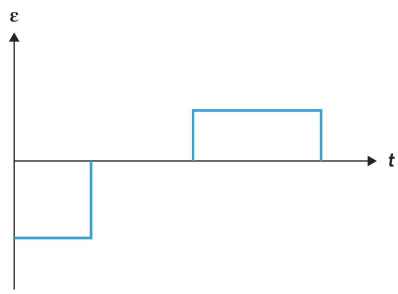


Which of the following graphs shows the resulting EMF within the coil of wire over time?

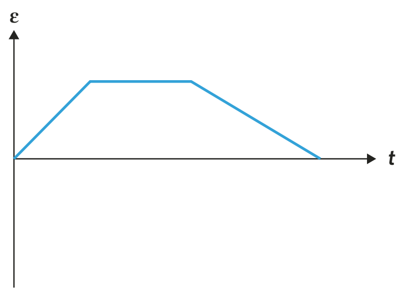
A



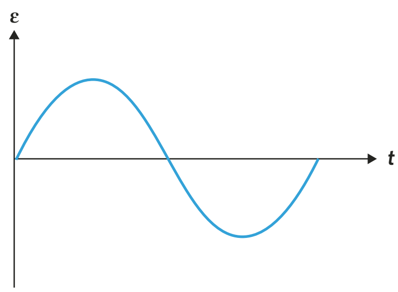
B



C



D



Adapted from 2017 VCAA Exam Section A Q6

Question 2

The owner of a Commodoré wishes to power a mini-fridge on the passenger seat of his car so he can store refreshing beverages at the worksite. To do this the voltage output of the car's alternator must be increased. Which of the following changes would increase the alternator voltage?

A Reduce the number of loops in the alternator.

B Reduce the area of the alternator's coils.

C Increase the period of rotation of the alternator.

D Use stronger magnets in the alternator.

Question 3

Physics students Kath and Kim are investigating the concept of electromagnetic induction and use a DC generator in their experiment. They measure the peak EMF produced in the generator whilst changing the strength of the magnetic field by the use of variable electromagnets. Which of the following options **best** identifies the independent variable, dependent variable, and a possible controlled variable in Kath and Kim's experiment?

	Independent variable	Dependent variable	Controlled variable
A	Period of rotation	Peak EMF	Strength of the magnetic field
B	Strength of the magnetic field	Period of rotation	Peak EMF
C	Strength of the magnetic field	Peak EMF	Period of rotation
D	Peak EMF	Strength of the magnetic field	Strength of the magnetic field

Adapted from 2018 VCAA Exam Section A Q20

Question 4

A generator is required to produce an average EMF of 5.5 V per quarter rotation (from a position of maximum magnetic flux to zero flux). The generator consists of 150 coils of wire that rotate at a frequency of 15.0 Hz and each has an area of 0.20 m^2. What is the strength of the magnetic field that must pass through each coil?

A 3.1 mT

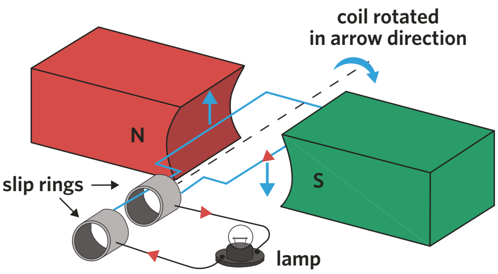
B 4.3 mT

C 0.55 T

D 2.8 T

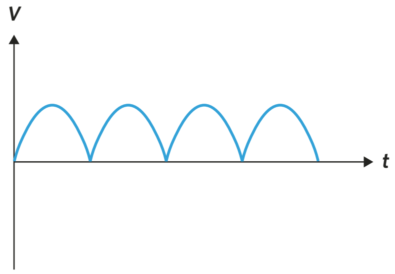
Question 5

The diagram depicts a generator being used to power a lamp.

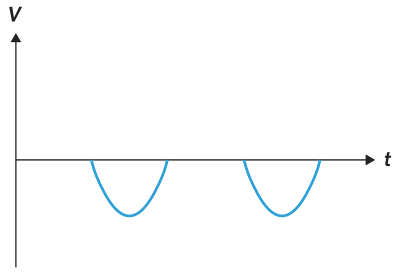


Which of the following graphs correctly shows how the output voltage of the generator varies as a function of time?

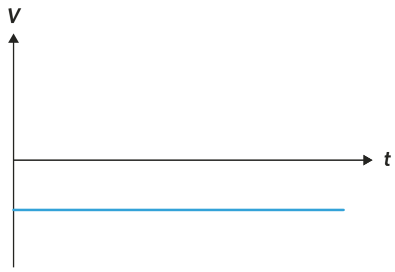
A



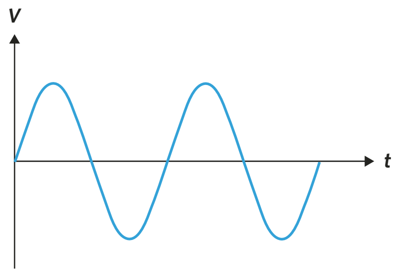
B



C



D



Adapted from 2015 VCAA Exam Section A Q12b

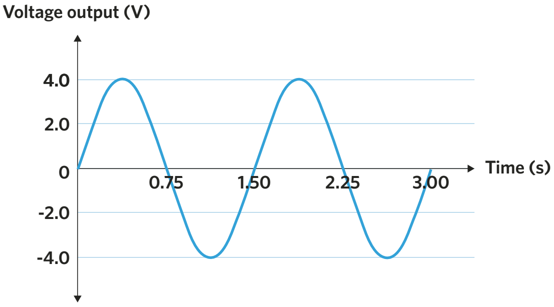
SECTION B

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)

Use the graph, which shows the output of a simple AC alternator, to complete the accompanying table.



Property	Value (with units)
Period	
Amplitude	
Frequency	

Question 7 (5 MARKS)

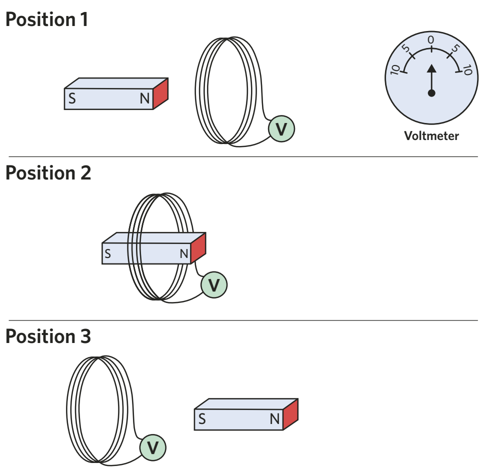
Latifa has her phone charger plugged into an AC generator, but her phone is charging too slowly. She decides to change four different properties of the generator to try to increase charging speed. For each change, state whether it will increase, decrease, or not change the peak EMF produced by the generator.

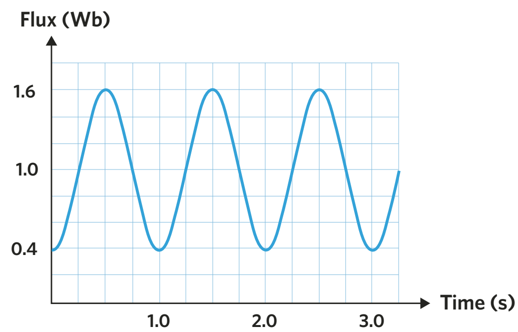
Change	Impact on peak EMF (increase, decrease or no change)
Increase the period of the generator coil's rotations.	
Increase the magnetic field strength.	
Increase the number of turns in the generator coil.	
Increase the resistance of the phone charger circuit.	
Increase the cross-sectional area of the generator coil.	

Adapted from 2016 VCAA Exam Section A Q17d

Question 8 (12 MARKS)

In Luke's backyard, three friends are goofing around with a bar magnet and a coil that has 4 loops of wire. They connect a voltmeter to the coil and oscillate the magnet from position 1 to position 3 and then back again.





The friends decide to calculate and graph magnetic flux as a function of time, as shown in the graph.

a Calculate the magnitude of the average current through the coil between 2.0 s and 2.5 s. The resistance of the coil is known to be 0.80 Ω. (3 MARKS)

b Use the information from the graph to determine the times after $t = 0$ s and before $t = 3.0$ s when the magnitude of the EMF around the coil will be a maximum. (2 MARKS)

c When the bar magnet is moved from position 1 to position 2 a current is induced in the coil. Use a sketch or words to describe the direction of this current when viewed from the right. Explain your answer carefully. (4 MARKS)

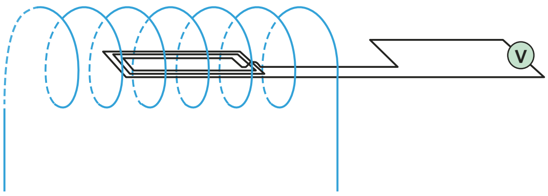
d Using the previous graph, complete the table to identify at what times between $t = 0$ s and before $t = 3.0$ s the magnet is at position 1, position 2, and position 3. (3 MARKS)

Position of the magnet	Time (s)
Position 1	0
Position 2	
Position 3	

Adapted from 2013 VCAA Exam Section A Q17

Question 9 (2 MARKS)

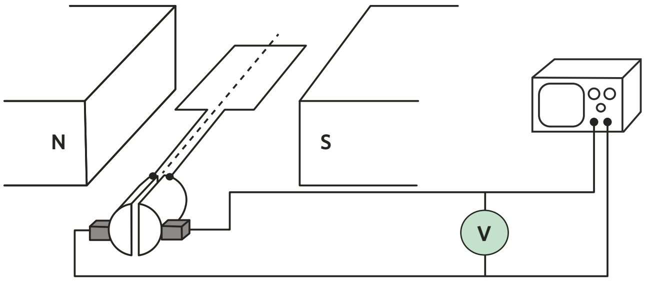
A square loop of wire connected to a voltmeter is placed inside of a solenoid. The square is comprised of 6 loops of wire and has an area of 0.10 m^2. The square loop is moved from outside of the solenoid to the inside in 0.25 s where there is a magnetic field of 300 mT.



What is the value of the magnetic flux passing through the square loop of wire? Explain your answer.

Question 10 (15 MARKS)

The DC generator in the diagram is comprised of a rectangular coil with 5 turns and sides 20 cm × 30 cm. The flux through the coil when in a vertical position is 0.15 Wb and it rotates 8.0 times every second.



a What is the strength of the uniform magnetic field? Include an appropriate unit. (3 MARKS)

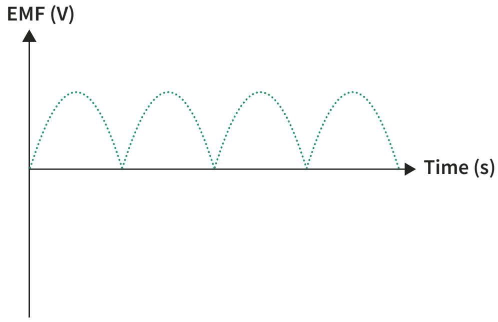
b What is the magnitude of the average EMF generated in the coil during a quarter rotation from a horizontal position to a vertical position? (3 MARKS)

c Describe how the magnetic flux through the coil changes as it completes one revolution from the horizontal position. (3 MARKS)

d Identify which orientation(s) of the coil during its rotation correspond to the maximum EMF. Explain your answer. (2 MARKS)

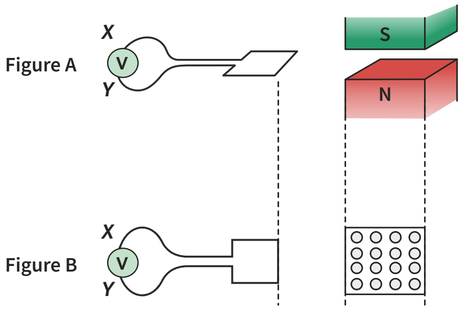
e Explain how the generator can be changed to produce an AC output. (2 MARKS)

f A graph of the output for the DC generator is shown with a dotted line. On a copy of this diagram, use a solid line to draw the output when this generator is converted to an AC alternator. (2 MARKS)



Question 11 (8 MARKS)

A square loop of wire is passed through the ends of two magnets at a constant speed in order to investigate electromagnetic induction. Figure B shows the apparatus when viewed from above. Consider the magnetic field as being confined to the space between the two magnets.

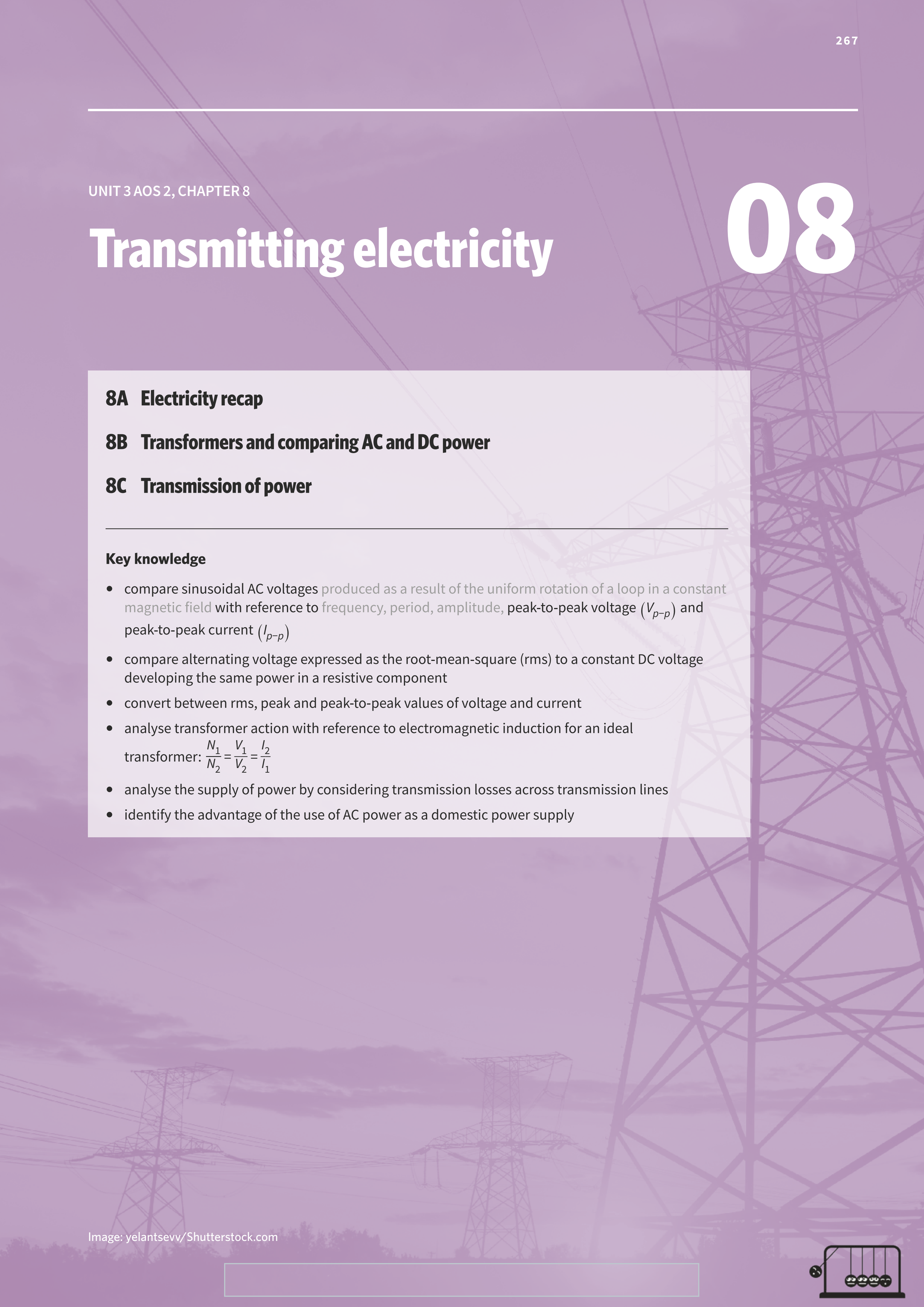


a Sketch the magnetic flux versus time graph for this scenario. Begin with the loop completely outside the magnetic field and finish with the entire loop having exited the magnetic field. (2 MARKS)

b Sketch the EMF versus time graph for this scenario. Begin with the loop completely outside the magnetic field and finish with the entire loop having exited the magnetic field. (2 MARKS)

c As the loop enters the magnetic field, determine the direction that the current passes through the voltmeter, either from *X* to *Y* or from *Y* to *X*. Explain your answer. (4 MARKS)

Adapted from 2015 VCAA Exam Section A Q13



UNIT 3 AOS 2, CHAPTER 8

08 Transmitting electricity

Key knowledge

- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})
- compare alternating voltage expressed as the root-mean-square (rms) to a constant DC voltage developing the same power in a resistive component
- convert between rms, peak and peak-to-peak values of voltage and current
- analyse transformer action with reference to electromagnetic induction for an ideal transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$
- analyse the supply of power by considering transmission losses across transmission lines
- identify the advantage of the use of AC power as a domestic power supply

8A ELECTRICITY RECAP

The content in this lesson is considered fundamental prior knowledge from Unit 1. It can be used as revision or to bridge understanding for students who have not studied Unit 1 Physics. This lesson revises knowledge of Ohm's law, circuit components like resistors and batteries, series circuits, and electric power.

8A Electricity recap	8B Transformers and comparing AC and DC power	8C Transmission of power

Key knowledge units	
Electrical quantities	1.2.1.1
Ohm's law	1.2.6.1
Series circuits	1.2.6.2
Power in electric circuits	1.2.11.1

Formulas for this lesson

Previous lessons		New formulas
3B	$P = \frac{\Delta E}{\Delta t}$	* $V = RI$
		* $P = VI = I^2R = \frac{V^2}{R}$
		* $R_T = R_1 + R_2 + \ldots + R_n$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

current (electric) the rate of flow of electric charge

potential difference see voltage

resistance (electrical) a measure of the opposition to the flow of electric current

resistor an electrical component that resists the flow of electric current and causes a drop in voltage. Components such as light bulbs and heaters can be modelled as resistors

series circuit an electric circuit where components are connected one after the other so that there is only one path along which charge can flow

voltage a measure of the change in the stored electrical energy per unit charge associated with the difference between two positions in an electric field

Electrical quantities 1.2.1.1

OVERVIEW

Electric charge is the fundamental quantity of electricity. Electric current is a measure of the rate of flow of electric charge through a medium when there is a voltage (potential difference) between two locations.

THEORY DETAILS

Current

- The fundamental quantity of electricity is the electric charge (Q), which is a property of subatomic particles like electrons and protons.
  - The unit of charge is the coulomb (C).
- Electric current (I) is a measure of the rate of flow of electric charge $\left(I = \frac{\Delta Q}{\Delta t}\right)$. In a wire, it is the movement of electrons which creates a current.
  - The unit of current is the ampere (A).

Voltage

- An electric field exists between any two locations where there is a difference in the concentration of charge. Similar to the stored energy for an object with mass in a gravitational field, electrical energy is stored due to the position of a charged object in an electric field.
- The voltage or potential difference (V) is a measure of the difference in the stored energy per unit of charge $\left(V = \frac{\Delta E}{\Delta Q}\right)$ between locations.
  - The unit of voltage is the volt (V), which is equivalent to 1 joule per coulomb (J C^{-1}).
- The existence of a potential difference in a circuit causes charge to flow (i.e., it causes a current) in a similar way to a gravitational field causing objects with mass to 'flow' by falling towards the ground.
- Voltages can be created by things like batteries, generators (explored in chapter 7), and physical processes like storms.

Resistance

- Resistance (R) measures an electrical component's opposition to the flow of current through it.
  - The unit of resistance is the ohm (Ω).
- Electrical circuits often contain resistors, which are components that have the purpose of resisting current flow to affect the electrical behaviour of the circuit.

Ohm's law 1.2.6.1

OVERVIEW

Ohm's law defines the relationship between the voltage across an electrical component, the current through the component, and the resistance of the component.

THEORY DETAILS

Ohm's law provides the basis of circuit analysis. Using this equation determines the amount of current that will flow through a circuit if we apply a certain voltage. Note that this relationship is positive and linear: if we apply a higher voltage across a resistor, a higher current will flow.

$$V = RI$$

V = voltage between two points in a circuit (V), R = resistance between the two points (Ω), I = current flow between the two points (A)

Series circuits 1.2.6.2

OVERVIEW

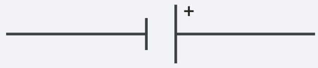
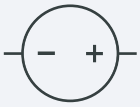
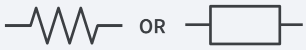
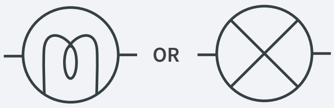
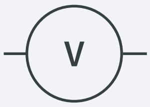
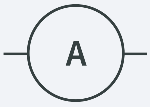
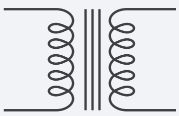
Series circuits are circuits where all components are connected one after the other by a single wire. The current is the same through the whole circuit and we model it as flowing from the positive terminal to the negative terminal of the voltage source. This is the opposite direction to the motion of electrons. The sum of the voltages across each component in the series circuit must be equal to the voltage supply.

THEORY DETAILS

Circuit components

When drawing circuits, each component is represented by a circuit symbol.

Table 1 Symbols used to represent circuit components in circuit diagrams

Circuit component	Circuit symbol
Wire	
Cell (a type of DC voltage source)	
Battery cell (a series of cells, which is also a DC voltage source)	
A general DC voltage source	
A general AC voltage source	
Resistor	
Light bulb	
Switch	
Voltmeter (measures voltage)	
Ammeter (measures current)	
Transformer	

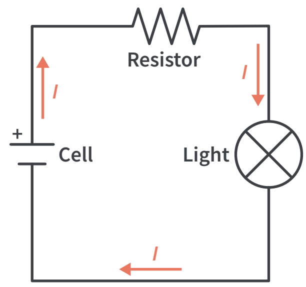


Figure 1 A series circuit consisting of a cell, a resistor, and a light bulb. The cell is a voltage source. The resistor and the light bulb limit the current flow and dissipate the electrical energy as heat (and light, in the case of the bulb). The current is constant throughout the circuit.

Resistors in series

The total resistance of n resistors connected in series is the sum of their individual resistances.

$$R_T = R_1 + R_2 + ... + R_n$$

R = resistance (Ω)

According to Ohm's law, $I = \frac{V}{R}$. Since there is only one path along which charges can flow in a series circuit, the current at all positions in the series circuit is the same (see Figure 1). This means the ratio $\frac{V}{R}$ will be constant in a given series circuit. When calculating the current this way, we must carefully choose the voltage and resistance between **the same two points** (see Worked example 1).

Due to the law of energy conservation, the total voltage supplied to a circuit (by the cell, for example) must be equal to the total voltage used around the circuit (the sum of the voltage drops across each component in the circuit). See Figure 2.

$$V_{supply} = V_1 + V_2 + ... + V_n$$

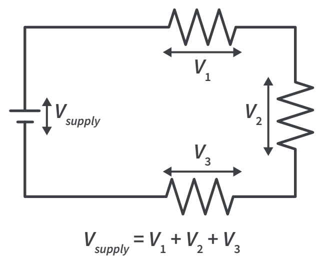
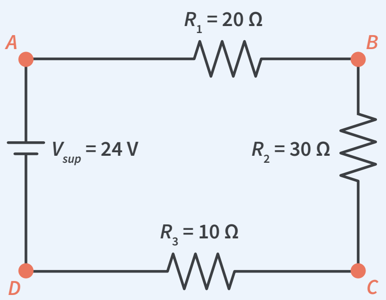


Figure 2 The voltage supplied to a circuit is equal to the total voltage drop around the circuit.

1 Worked example



a **Calculate the total resistance of the resistors in this series circuit.**

b **The cell provides a voltage of 24 V. Determine the current that flows around the circuit.**

c **Calculate the voltage drop across each resistor.**

a $R_T = R_1 + R_2 + R_3$

$R_T = 20 + 30 + 10 = 60\ \Omega$

b To calculate the current, we need to apply Ohm's law. At this stage, the only voltage we know is the supply voltage of 24 V. This voltage applies between points *A* and *D*, so we must use the corresponding resistance between points *A* and *D*, which is the total resistance.

$V_{AD} = R_{AD}I$

$24 = 60 \times I$

$I = 0.40$ A

c Again, we need to apply Ohm's law to calculate the voltage drop across each resistance. Now, we know the current (which is the same for all resistors) and we must use the resistance of each resistor to calculate the corresponding voltage drop.

For resistor 1, between points *A* and *B*:
$V_{AB} = R_{AB}I = 20 \times 0.40 = 8.0$ V

For resistor 2, between points *B* and *C*:
$V_{BC} = R_{BC}I = 30 \times 0.40 = 12$ V

For resistor 3, between points *C* and *D*:
$V_{CD} = R_{CD}I = 10 \times 0.40 = 4.0$ V

Notice that the sum of the voltage drop across each resistor is equal to the voltage supply: $24 = 8.0 + 12 + 4.0$.

Power in electric circuits 1.2.11.1

OVERVIEW

Power is the rate that energy is delivered or dissipated. Power in electric circuits is delivered by sources like batteries and dissipated by components such as resistors and light bulbs.

THEORY DETAILS

As explored in lesson 3B, power is the rate of change of energy with respect to time.

$$P = VI$$

P = power (W), V = voltage (V), I = current (A)

This formula can be understood by recognising $V = \frac{\Delta E}{\Delta Q}$ and $I = \frac{\Delta Q}{\Delta t}$. Hence $VI = \frac{\Delta E}{\Delta Q} \times \frac{\Delta Q}{\Delta t} = \frac{\Delta E}{\Delta t}$.

The voltage used to calculate power for one or more electrical components is the **voltage over those components**.

By substituting Ohm's law into the electric power equation, we can also calculate power using:

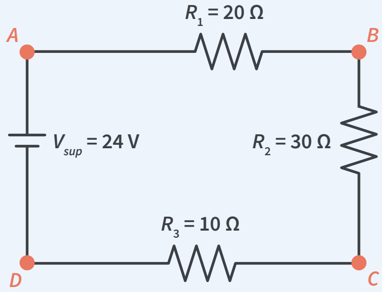
$$P = I^2R = \frac{V^2}{R}$$

P = power (W), I = current (A), R = resistance (Ω), V = voltage (V)

USEFUL TIP

Make sure that the voltage and resistance you use in a power calculation for one or more components is the voltage and resistance for those components only.

2 **Worked example**



a **Calculate the total power dissipated by this circuit, given that the current is 0.40 A and $R_T = 60\ \Omega$.**

b **Determine the power dissipated by each resistor.**

a Power is dissipated by the resistors between points *A* and *D*.

There is a total of 24 V applied across the resistors.

$P_{AD} = V_{AD}I = 24 \times 0.40 = 9.6$ W

OR

$P_{AD} = I^2R_{AD} = 0.40^2 \times 60 = 9.6$ W

OR

$P_{AD} = \frac{{V_{AD}}^2}{R_{AD}} = \frac{24^2}{60} = 9.6$ W

b For resistor 1: $P_{AB} = I^2R_{AB} = 0.40^2 \times 20 = 3.2$ W

For resistor 2: $P_{BC} = I^2R_{BC} = 0.40^2 \times 30 = 4.8$ W

For resistor 3: $P_{CD} = I^2R_{CD} = 0.40^2 \times 10 = 1.6$ W

Each of these values could also have been calculated by using the voltage drop across each resistor, which was calculated in Worked example 1, and applying $P = VI$ or $P = \frac{V^2}{R}$.

Notice that the sum of the power dissipated in each resistor is equal to the total power supplied/dissipated: 9.6 = 3.2 + 4.8 + 1.6.

Theory summary

- Current is the rate of flow of charge with respect to time.
- A voltage causes a current to flow in a circuit.
- A resistance opposes the flow of current.
- Ohm's law $V = RI$ relates the voltage across a resistor to the current through it.
- Current is constant around a series circuit.
- The total resistance of resistors in series is the sum of their individual resistances.
- The total voltage supplied must equal the total voltage drop around a circuit.
- Power is dissipated by resistors and delivered by sources.

KEEN TO INVESTIGATE?

PhET 'Charges and Fields' simulation
https://phet.colorado.edu/en/simulation/charges-and-fields

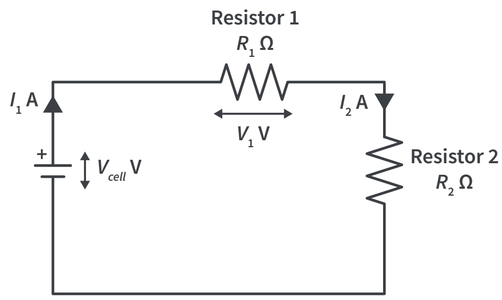
PhET 'Circuit Construction Kit' simulation
https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc

YouTube video: Engineering Mindset – How Electricity Works
https://youtu.be/mc979OhitAg

8A Questions

THEORY REVIEW QUESTIONS

Use the following information to answer Questions 1–4.



Question 1

The power dissipated by Resistor 1 is equal to I_1 multiplied by

A V_{cell}

B R_1

C V_1

D R_2

Question 2

The current I_2 is equal to

A I_1

B $\frac{V_{cell}}{I_1}$

C $\frac{V_{cell}}{R_1}$

D $\frac{V_{cell}}{R_2}$

Question 3

The power supplied by the cell is equal to

A I_1

B $V_{cell} \times I_1$

C $\frac{V_{cell}^2}{R_1}$

D $I_1^2 \times R_1$

Question 4

The total resistance of the circuit is

A R_1

B $R_1 + R_2$

C $\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$

D $\frac{1}{R_1} + \frac{1}{R_2}$

Question 5

Which of these statements is **incorrect**?

A Current is the rate of flow of charge.

B Current flows due to a potential difference.

C Resistors dissipate power from a circuit.

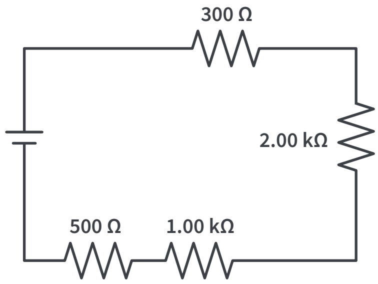
D Power is the amount of energy in a circuit.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

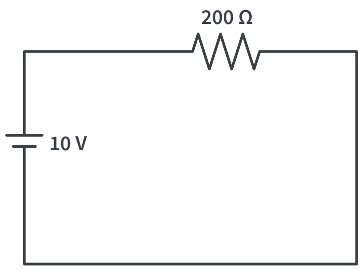
Calculate the total resistance in the following circuit.



Question 7 (1 MARK)

A current of 5.0 A is flowing from a 9.0 V battery cell through a series circuit. What is the resistance of this circuit?

Question 8 (2 MARKS)



a 10 V is applied across a 200 Ω resistor as shown. Determine the current that will flow through the resistor. (1 MARK)

b Determine the power dissipated by the 200 Ω resistor. (1 MARK)

Question 9 (2 MARKS)

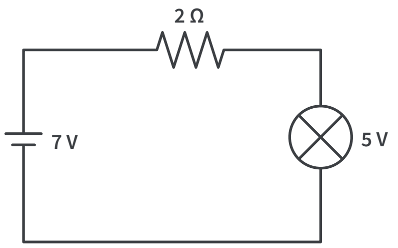
10 A is flowing through a 100 Ω resistor. How much energy is dissipated by the resistor in 10 seconds?

Question 10 (2 MARKS)

A 200 Ω resistor dissipates 30 W of power. What is the voltage across the resistor?

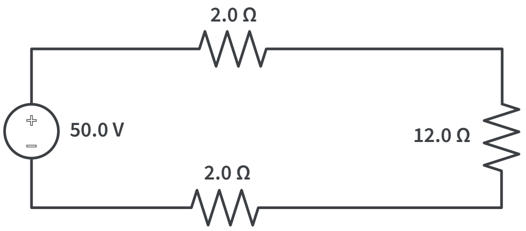
Question 11 (2 MARKS)

The light globe in the circuit diagram operates correctly when there is a potential difference of 5 V across it. Determine the power dissipated by the light bulb when it is operating correctly.



Question 12 (6 MARKS)

Consider the circuit shown.



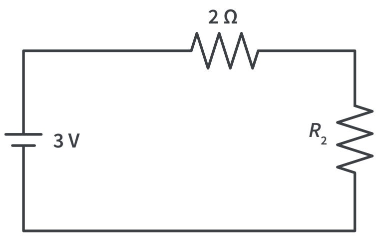
a Determine the total power dissipated in this series circuit. (2 MARKS)

b Calculate the voltage drop across the 12 Ω resistor. (2 MARKS)

c What is the total power dissipated by the two 2.0 Ω resistors? (2 MARKS)

Question 13 (3 MARKS)

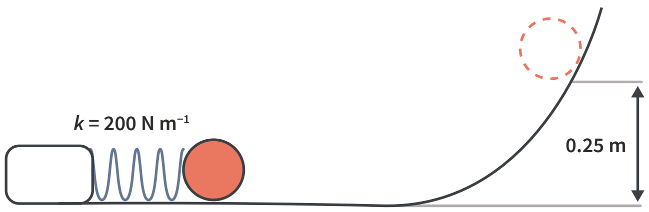
12 J of energy is delivered by this circuit's 3 V cell in 4 seconds. Determine the resistance of R_2.



Previous lessons

Question 14 (4 MARKS)

A ball with a mass of 0.1 kg is launched from a compressed horizontal spring with a spring constant of 200 N m^{-1}. The ball then rolls up a ramp to a height of 0.25 m. Ignore the effects of resistance forces in this question.



a Show that the spring was initially compressed by 0.05 m (to one significant figure). (2 MARKS)

b Calculate the speed of the ball immediately after leaving the spring. (2 MARKS)

Question 15 (3 MARKS)

An electron is placed at a distance of 10 metres from particle with a positive charge of 5.0×10^{-15} C and a mass of 8.0×10^{-30} kg. Calculate the magnitude of the acceleration of the electron due to the electric field created by the positive charge. Take the charge on an electron to be -1.6×10^{-19} C and the mass of the electron to be 9.1×10^{-31} kg.

Key science skills

Question 16 (5 MARKS)

An experiment is conducted to investigate Ohm's law using a resistor and a variable voltage that is applied across the resistor. The resulting current is measured.

a Represent the following data on a graph. Include an appropriate scale, labelled axes, and a line of best fit. (3 MARKS)

Voltage (V)	Current (A)
20	2.2
60	6.0
75	7.3
90	9.2

b Use the gradient to determine the resistance of the resistor. (2 MARKS)

8B TRANSFORMERS AND COMPARING AC AND DC POWER

In this lesson we will explore the similarities and differences between AC and DC power. We will also draw upon our understanding of electric and magnetic fields to understand how electrical transformers work, and why they rely on a changing current.

8A Electricity recap	8B Transformers and comparing AC and DC power	8C Transmission of power

Study design key knowledge dot points

- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage ($V_{p\text{-}p}$) and peak-to-peak current ($I_{p\text{-}p}$)
- compare alternating voltage expressed as the root-mean-square (rms) to a constant DC voltage developing the same power in a resistive component
- convert between rms, peak and peak-to-peak values of voltage and current
- analyse transformer action with reference to electromagnetic induction for an ideal transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$

Key knowledge units

RMS, peak, and peak-to-peak values of an AC supply	3.2.4.2 & 3.2.6.1
Comparing RMS and DC power	3.2.5.1
Transformers	3.2.7.1

Formulas for this lesson

Previous lessons		New formulas
8A	* $V = RI$	* $\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$
8A	* $P = VI = I^2R = \frac{V^2}{R}$	* $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$
		* $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

AC (alternating current) electricity electricity with a periodically alternating direction of current and voltage

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

transformer a device that uses electromagnetic induction to transfer power from one electrical circuit to another, commonly with an exchange of current for voltage, or vice versa, while (ideally) keeping the power constant

RMS, peak, and peak-to-peak values of an AC supply 3.2.4.2 & 3.2.6.1

OVERVIEW

We have three alternative ways of describing the magnitude of the voltage or current of AC electricity: RMS, peak, and peak-to-peak.

THEORY DETAILS

AC (alternating current) electricity describes electricity with a changing direction of current and voltage. It is common for the voltage and current of AC electricity to vary sinusoidally with time (see Figure 1). This means that the voltage, current, and power are constantly changing from one moment to the next.

For AC electricity that has a time-varying sinusoidal shape, we can apply three alternative descriptions – RMS, peak, and peak-to-peak – to **both voltage and current** in a similar way:

- The peak value describes the amplitude (maximum value) of the voltage or current.
- The peak-to-peak value describes the difference between the maximum and the minimum values.
- The RMS value is a fixed proportion of the peak value, and its use will be explained in the next section.

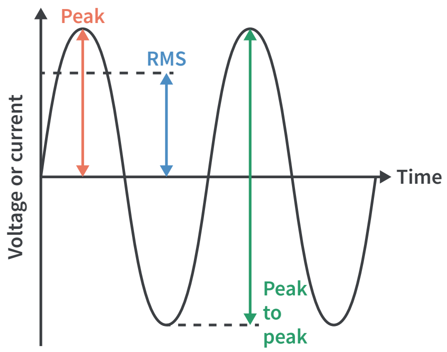


Figure 1 A voltage (or current) against time graph with indications of peak, peak-to-peak, and RMS values.

RMS values are related to peak values 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)

From Figure 1, we can see that the peak-to-peak value is double the peak value:

$V_{p-p} = 2 \times V_{peak}$

$I_{p-p} = 2 \times I_{peak}$

USEFUL TIP

The RMS value is always less than the corresponding peak value. It can help to keep this in mind to check the appropriateness of your calculations.

1 **Worked example**

a **Convert 170 V_{peak} to an RMS value.**

b **Convert 34.0 A_{RMS} to a peak-to-peak value.**

a $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak} = \frac{1}{\sqrt{2}} \times 170 = 120\text{ V}$

b $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$ $\therefore 34.0 = \frac{1}{\sqrt{2}} \times I_{peak}$

$I_{peak} = 48.08\text{ A}$

$I_{p-p} = 2 \times I_{peak} = 2 \times 48.08 = 96.2\text{ A}$

Comparing RMS and DC power 3.2.5.1

OVERVIEW

RMS values of voltage and current are used to compare DC and AC power sources.

THEORY DETAILS

The RMS values of AC voltage and current allow us to easily compare the power delivered by AC electricity with the power delivered by DC electricity. An RMS value is a measure of a time-varying (AC) voltage or current, which has the same magnitude as the constant DC value that would deliver the same amount of power.

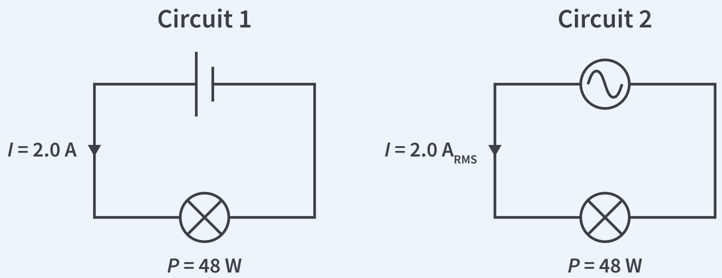
For example, consider a light bulb rated at 12 V. If we use a DC source, such as a battery, to supply power to the light bulb, we would require a constant 12 V source for the light bulb to operate properly. To deliver the same power to the same light with an AC source, we require a 12 V_{RMS} AC source, which has a peak value of 17 V (to two significant figures).

The average power delivered by AC electricity can be calculated from the RMS values of voltage and current by using the same formulas that we would use for DC electricity.

$$P = V_{RMS} I_{RMS} = I_{RMS}^2 R = \frac{V_{RMS}^2}{R}$$

2 **Worked example**

Consider the two electrical circuits shown. In Circuit 1, a cell is producing 2.0 A which supplies 48 W to a light bulb. In Circuit 2, an AC source is producing 2.0 A_{RMS} which supplies 48 W to a light bulb.



a **Calculate the voltage delivered by the cell in Circuit 1.**

b **Calculate the peak voltage in the Circuit 2.**

a Cells produce DC electricity so we do not need to convert between peak and RMS values.

$P = VI \ \therefore 48 = V \times 2.0$

$V = 24$ V

b We know that DC voltage is equivalent to AC RMS voltage.

So from part **a**:

$V_{RMS} = 24$ V

Now we need to convert from RMS to peak voltage.

$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak} \ \therefore 24 = \frac{1}{\sqrt{2}} V_{peak}$

$V_{peak} = 34$ V

Transformers 3.2.7.1

OVERVIEW

Transformers are devices that transfer electric power between circuits, usually whilst increasing the voltage and decreasing the current, or vice versa. They operate using Faraday's principle of electromagnetic induction, which means that they require changing currents to operate effectively.

THEORY DETAILS

A basic transformer consists of two coils of wire wrapped around the same iron core (see Figure 2) and it operates as follows (see Figure 3).

- When an **AC current** passes through one of the coils (known as the 'primary coil'), it produces a **changing magnetic field**.
- The magnetic field produced by the primary coil is guided through the secondary coil by the iron core.
- Hence, there is a **changing magnetic flux** through the secondary coil.
- An EMF, and hence a current, is induced in the secondary coil as a result of the changing magnetic flux, as described by Faraday's law $\left(EMF = -N\frac{\Delta\Phi_B}{\Delta t}\right)$.

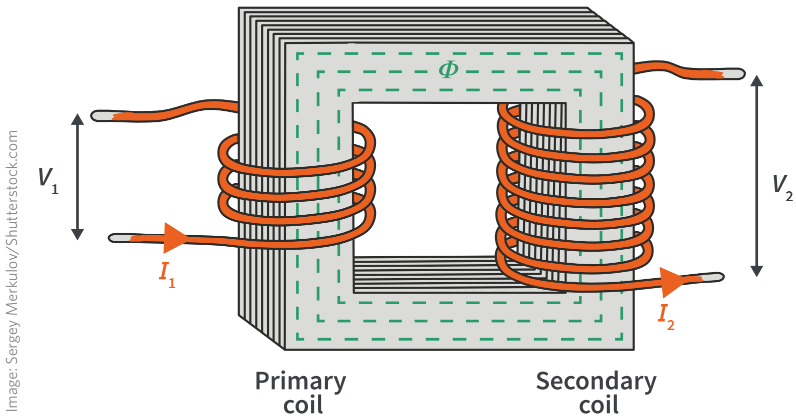


Figure 2 The primary and secondary coils of a step-up transformer

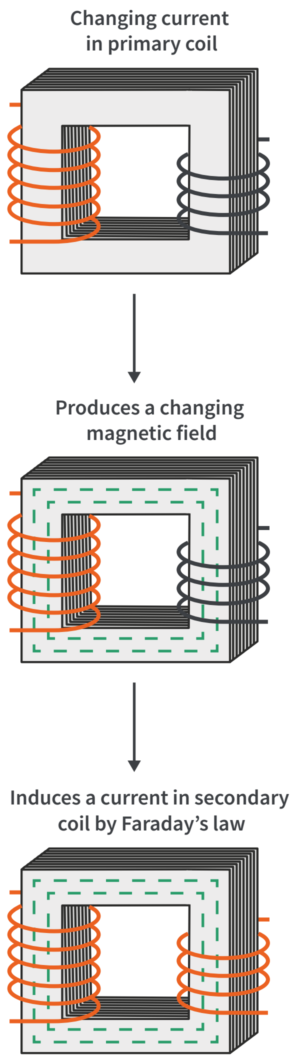


Figure 3 The steps involved in transformer action due to electromagnetic induction

It is important to recognise the role of the changing current in the primary coil in transformer operation. If a **constant DC supply** were used, then the magnetic flux in the secondary coil would also be constant, which means that **no EMF would be induced in the secondary coil**.

The primary coil always refers to the coil on the power supply side. The ratio of the voltage in the primary coil (V_1) to the voltage induced in the secondary coil (V_2) is equal to the ratio of the number of turns in the primary coil (N_1) to the number of turns in the secondary coil (N_2).

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

In VCE Physics we will model the transformer as ideal, which means that all of the power delivered to the primary coil is transferred to the secondary coil. Hence:

$$P_1 = P_2 \text{ so } V_1 I_1 = V_2 I_2$$

This yields the following relationship. Note that the ratio of currents has the secondary current as the numerator of the fraction.

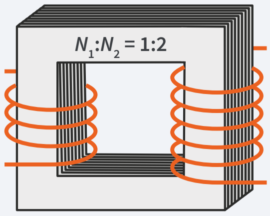
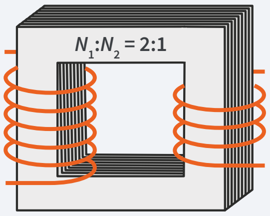
$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

N_1 = turns in the primary side (no units), N_2 = turns in the secondary side (no units), V_1 = primary voltage (V), V_2 = secondary voltage (V), I_2 = secondary current (A), I_1 = primary current (A)

A **step-up** transformer is one where the voltage in the secondary side is greater than the voltage in the primary side.

A **step-down** transformer is one where the voltage in the secondary side is less than the voltage in the primary side.

Table 1 The properties of step-up and step-down transformers

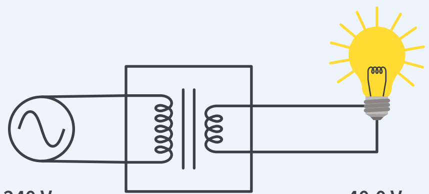
Type	Voltage	Current	Example
Step-up $N_1 < N_2$	Increases $V_1 < V_2$	Decreases $I_1 > I_2$	
Step-down $N_1 > N_2$	Decreases $V_1 > V_2$	Increases $I_1 < I_2$	

USEFUL TIP

We can use RMS, peak, or peak-to-peak voltages and currents in transformer calculations but we must consistently use the same type. For example, we will calculate an incorrect ratio if we use RMS voltage for the primary coil and the peak voltage for the secondary coil.

3 Worked example

Consider the electrical circuit shown, which consists of a 240 V_{RMS} AC power supply connected to a 40.0 V light bulb that is operating correctly. Assume that the connecting wires have negligible resistance.



a **Which type of transformer – step-up or step-down – is being used?**

b **The primary coil of the transformer has 600 turns in it. How many turns does the secondary coil have?**

c **Considering the current in the primary coil is 12 A_{peak}, determine the peak current in the secondary coil.**

a The statement that the 40.0 V_{RMS} light bulb is 'operating correctly' indicates that there is a voltage of 40.0 V_{RMS} across it. Since the wires have negligible resistance, we can assume that the voltage in the primary coil is the same as the voltage supply and that the voltage in the secondary coil is the same as the voltage across the light bulb.

This means that the voltage decreases from 240 V_{RMS} on the primary side to 40.0 V_{RMS} on the secondary side, so the transformer is a step-down transformer.

b Taking $N_1 = 600$, $V_1 = 240$ V and $V_2 = 40.0$ V:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \therefore \frac{600}{N_2} = \frac{240}{40.0}$$

$N_2 = 100$ turns in the secondary coil.

c As we are solving for a peak current and we have been given a peak current value, we can apply the transformer ratios without making any conversions.

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \therefore \frac{600}{100} = \frac{I_2}{12}$$

$I_2 = 72\ A_{peak}$

Theory summary

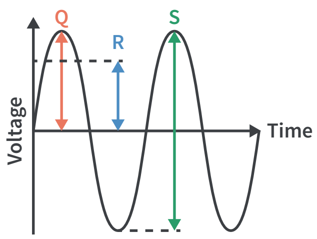
- RMS and peak values of voltage and current for AC electricity are related by:
  - $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$ and $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$
- For AC electricity, the values of RMS voltage and current indicate the values of a constant DC voltage and current that would deliver the same average power.
- Transformers operate through the principle of electromagnetic induction and are used to change the voltage and current.
  - They require a changing current in the primary coil to operate effectively.
  - Ideal transformers have the same power on the primary and secondary sides so that the primary and secondary coils are related by: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$.

8B Questions

THEORY REVIEW QUESTIONS

Question 1

Identify the arrows in the diagram that represent the RMS, peak, and peak-to-peak voltages.



	Q	R	S
A	Peak-to-peak	Peak	RMS
B	Peak-to-peak	RMS	Peak
C	Peak	RMS	Peak-to-peak
D	RMS	Peak-to-peak	Peak

Use the following information to answer Questions 2–4.

An ideal transformer has $N_1 = 50$ turns in the primary coil and $N_2 = 100$ turns in the secondary coil.

Question 2

Which option best describes the transformer?

A Step-up

B Step-down

C Step-on

D Step-around

Question 3

What is the ratio of the voltage in the primary coil to the voltage in the secondary coil (V_1:V_2)?

A 1:1

B 1:2

C 2:1

D 2:2

Question 4

What is the ratio of the current in the primary coil to the current in the secondary coil (I_1:I_2)?

A 1:1

B 1:2

C 2:1

D 2:2

Question 5

Consider a **step-up** transformer that has a **constant DC power supply** connected to its primary coil such that the voltage in the primary coil is 20 V and the current is 0.1 A. What can be said about the voltage, current, and power in the **secondary coil**?

	Voltage	Current	Power
A	Greater than 20 V	Greater than 0.1 A	Greater than 2 W
B	Greater than 20 V	Less than 0.1 A	Equal to 2 W
C	Less than 20 V	Greater than 0.1 A	Equal to 2 W
D	Equal to 0 V	Equal to 0 A	Equal to 0 W

Question 6

Consider a **step-up** transformer that has an **AC power supply** connected to its primary coil such that the voltage in the primary coil is 20 V_{RMS} and the current is 0.1 A_{RMS}. What can be said about the voltage, current, and average power in the **secondary coil**?

	Voltage	Current	Power
A	Greater than 20 V_{RMS}	Greater than 0.1 A_{RMS}	Greater than 2 W
B	Greater than 20 V_{RMS}	Less than 0.1 A_{RMS}	Equal to 2 W
C	Less than 20 V_{RMS}	Greater than 0.1 A_{RMS}	Equal to 2 W
D	Equal to 0 V_{RMS}	Equal to 0 A_{RMS}	Equal to 0 W

EXAM-STYLE QUESTIONS

This lesson

Use the following information to answer Questions 7 and 8.

A speaker that requires 15 V_{RMS} AC to operate is supplied by a 345 V to 15 V transformer connected to a 345 V_{RMS} power supply.

Question 7 (1 MARK)

What is the ratio of the turns in the transformer's primary to secondary coils?

A 1:20

B 20:1

C 1:23

D 23:1

Question 8 (1 MARK)

The speaker is taken out of this circuit and is attached to a battery instead. The voltage required for the speaker to operate correctly is closest to

A 11 V.

B 15 V.

C 21 V.

D 23 V.

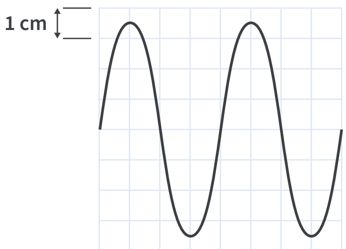
Adapted from 2019 VCAA NHT Exam Section A Q5 and Q6

Question 9 (1 MARK)

Alfie is working with a transformer that has 200 turns in the primary coil and 1200 turns in the secondary coil. The current in the secondary coil is 13.5 A_{RMS}. Calculate the current in the primary coil.

Question 10 (1 MARK)

Alice is measuring the voltage from an AC signal generator using an oscilloscope, which produces the following output. The vertical scale is set to 3.0 V cm^{-1}.



Which option best gives the value of the RMS voltage of the AC signal generator?

A 21 V

B 4.5 V

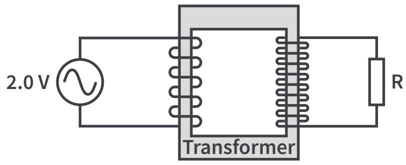
C 10.5 V

D 7.4 V

Adapted from 2010 VCAA Exam 1 Section B Detailed study 3 Q4

Question 11 (7 MARKS)

Ted is experimenting with an ideal transformer in the circuit shown.



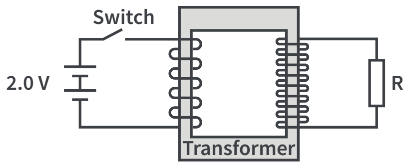
The primary coil has 500 turns; the secondary coil has 4000 turns. A 2.0 V_{RMS} AC power supply is connected across the primary coil and there is a 1000 Ω resistor in the secondary circuit.

a Calculate the RMS voltage across the resistor. (1 MARK)

b Calculate the peak voltage across the resistor. (1 MARK)

c Calculate the power dissipated in the resistor. (2 MARKS)

Ted modifies the circuit and connects a 2.0 V DC battery and a switch in the primary circuit as shown.



d Ted measures the current in the resistor as the switch is closed. Before the switch is closed, there is no current in the resistor. When the switch is closed, there is a very short pulse of current in the resistor. When the switch remains closed, there is no current in the resistor.

Explain why there is a short pulse of current as the switch is closed and why there is no current in the resistor as the switch remains closed. No numbers are required in your answer. (3 MARKS)

Adapted from 2013 VCAA Exam Section A Q15

Question 12 (4 MARKS)

Melanie is setting up a lamp for her desk. A variable AC power supply is connected to the primary side of a 15:1 transformer. The lamp is connected to the secondary side of the transformer.

a The voltage output of the secondary coil is 16.0 V_{RMS}. Calculate the peak voltage in the primary coil. (2 MARKS)

b The voltage in the secondary coil is increased to 20.0 V_{RMS}. Given that the resistance of the lamp in this situation is 10 Ω, calculate the RMS current in the primary coil. (2 MARKS)

Question 13 (3 MARKS)

Lily is setting up an amplifier that requires 144 W to operate correctly and it has a resistance of 36 Ω. It is connected to the secondary side of a transformer. The primary coil of the transformer has 500 turns and is connected to an AC power supply that is producing 18 V_{RMS}. Given that the amplifier is working correctly, determine the number of turns in the secondary coil.

Previous lessons

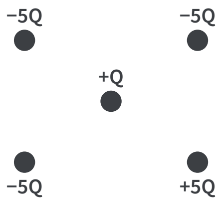
Question 14 (2 MARKS)

What is the first postulate of Einstein's theory of special relativity regarding inertial reference frames? Identify whether this concept differs from the descriptions of classical physics.

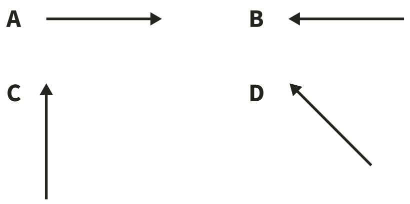
Adapted from 2019 VCAA Exam Section B Q11

Question 15 (1 MARK)

Four charges (–5Q, –5Q, –5Q, +5Q) are placed at the vertices of a square and a fifth charge (+Q) is placed at the centre of the square, as shown.



Which one of the following arrows best represents the direction of the net force on the charge +Q?



Adapted from 2019 VCAA Exam Section A Q3

Key science skills

Question 16 (1 MARK)

Lyn is taking measurements of the current flowing through a series circuit with a constant voltage supply. She notices that the value of the current on her ammeter is changing slightly. Her friend advises her to take five measurements of the current and then calculate the average. Which option best describes the benefit of taking multiple measurements and calculating an average?

A It reduces the systematic error in the experiment.

B It reduces the random error in the experiment.

C It reduces the uncertainty in each individual reading of the current.

D It reduces the effect of the random error, so the average value is likely to be more accurate.

8C TRANSMISSION OF POWER

This lesson will explore the way that transformers are practically applied to increase the efficiency of power transmission systems and identify the advantage of the use of AC power as a domestic power supply.

8A Electricity recap	8B Transformers and comparing AC and DC power	8C Transmission of power

Study design key knowledge dot points

- analyse transformer action with reference to electromagnetic induction for an ideal transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$
- analyse the supply of power by considering transmission losses across transmission lines
- identify the advantage of the use of AC power as a domestic power supply.

Key knowledge units

Power supply and transmission losses	3.2.8.1
Transformers in power transmissions	3.2.9.1

Formulas for this lesson

Previous lessons		New formulas
8A	* $V = RI$	* $V_{drop} = I_{line} R_{line}$
8A	* $P = VI = I^2 R$	* $P_{loss} = V_{drop} I_{line} = I_{line}^2 R_{line}$
8B	* $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

load (electrical) a part of an electrical circuit which consumes power

Power supply and transmission losses 3.2.8.1

OVERVIEW

Electrical power lines have a resistance which increases with their length. Hence, transmitting power over long distances results in a significant voltage drop and loss in power. For the purposes of VCE Physics, these power transmission systems can be modelled as simple series circuits.

THEORY DETAILS

A simple power transmission system (without transformers) consists of a power supply/generator, transmission lines, and a load as shown in Figure 1. For our purposes, the load is the part of the circuit for which the electrical power is intended, such as an appliance, a house, or a whole town. These transmission systems can be represented by a series circuit where the transmission lines, which have a small but not insignificant resistance, can be modelled as a single resistor as shown in Figure 2.

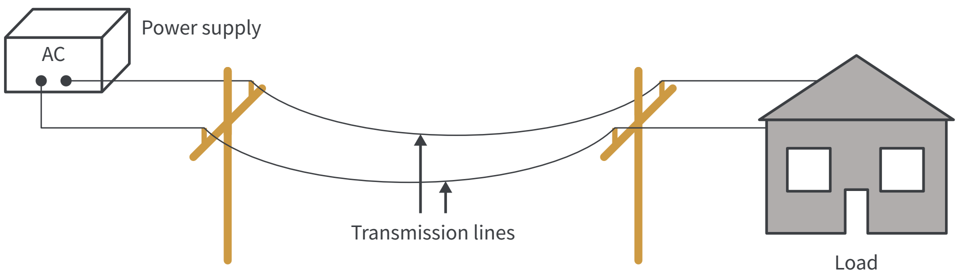


Figure 1 A simple power transmission system consists of the power supply, transmission lines, and a load.

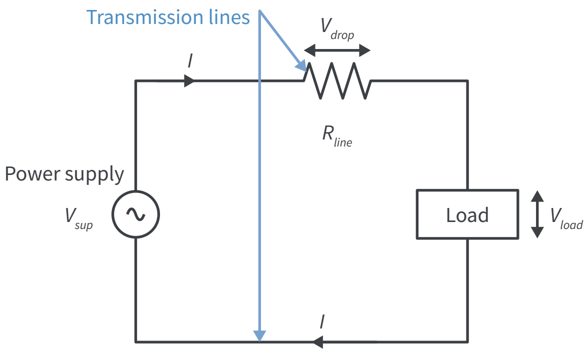


Figure 2 A circuit diagram for the transmission system from Figure 1. The resistance of the transmission lines is modelled as a resistor. Note that V_{sup} is equal to the RMS value of the AC power supply voltage.

USEFUL TIP

The resistance of the two transmission lines must be treated as a single resistance, as shown in Figure 2, **unless specified otherwise**. Sometimes an exam question will provide the resistance of each of the wires in the transmission lines seperately. We must use the **total** resistance of the transmission lines (the sum of the resistances of each wire) to calculate the voltage drop and power loss.

The resistance of the transmission lines causes a voltage drop across the lines which follows Ohm's law.

$$V_{drop} = I_{line} R_{line}$$

V_{drop} = voltage drop across the transmission lines (V), I_{line} = current in the transmission lines (A), R_{line} = resistance of the transmission lines (Ω)

In a simple transmission system **without transformers** the voltage that is delivered to the load will be the difference between the voltage supply and the voltage drop: $V_{load} = V_{sup} - V_{drop}$

The power loss due to the resistance in the transmission lines can be calculated using the relationships established in lesson 8A.

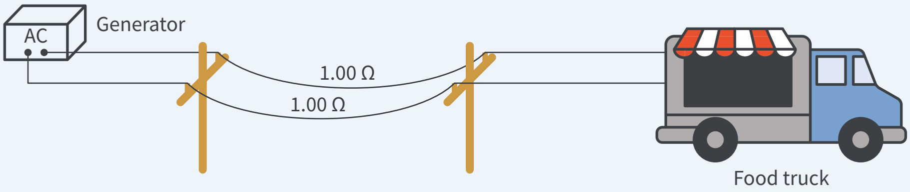
$$P_{loss} = V_{drop} I_{line} = I_{line}^2 R_{line}$$

P_{loss} = power loss in the transmission lines (W), V_{drop} = voltage drop across the transmission lines (V), I_{line} = current in the transmission lines (A), R_{line} = resistance of the transmission lines (Ω)

The power delivered to the load will be the difference between the power supply and the power loss: $P_{load} = P_{sup} - P_{loss}$. This relationship **also applies when transformers are included** in the transmission system.

1 Worked example

A generator is producing 200 W at 40.0 V_{RMS} which is used to supply a food truck. The transmission lines have a resistance of 1.00 Ω each.



a **Calculate the current in the transmission lines.**

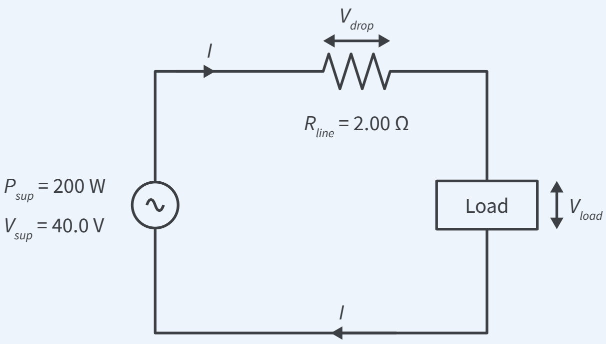
b **Calculate the voltage drop across the transmission lines.**

c **Calculate the power loss in the transmission lines.**

d **Calculate the voltage delivered to the food truck.**

e **Calculate the power delivered to the food truck.**

The transmission system can be modelled by a circuit diagram as shown.



a The power supply is the only part of the circuit about which we have enough information to calculate the current. This is the same as the current in the transmission lines.

$P = VI \ \therefore 200 = 40.0 \times I$

$I = 5.00$ A

b The voltage drop across the resistance lines depends on the total resistance of the lines.

$R_{line} = 1.00 + 1.00 = 2.00\ \Omega$

$V_{drop} = I_{line} R_{line} = 5.00 \times 2.00 = 10.0$ V

c $P_{loss} = V_{drop} I_{line} = 10.0 \times 5.00 = 50.0$ W

OR

$P_{loss} = I_{line}^2 R_{line} = 5.00^2 \times 2.00 = 50.0$ W

OR

$$P_{loss} = \frac{V_{drop}^2}{R_{line}} = \frac{10.0^2}{2.00} = 50.0 \text{ W}$$

d $V_{load} = V_{sup} - V_{drop} = 40.0 - 10.0 = 30.0$ V

e $P_{load} = P_{sup} - P_{loss} = 200 - 50.0 = 150$ W

OR

$P_{load} = V_{load} I_{load} = 30.0 \times 5.00 = 150$ W

Transformers in power transmission 3.2.9.1

OVERVIEW

AC power has an advantage over DC power for the transmission of electricity because transformers can be used. Using transformers means the current can be reduced in the transmission lines by stepping up the voltage. This reduces the voltage drop across the lines – which is proportional to current – and the power loss in the lines – which is proportional to the square of the current. This improves the overall efficiency of the power transmission system.

THEORY DETAILS

Advantage of AC power

This key knowledge unit explains how transformers can be used to reduce power loss in transmission. In lesson 8B we learned that transformers require a changing current. This means the benefit of transformers explained in this section applies to AC power but it does not apply to the transmission of constant DC power. For this reason, the advantage of AC power as a domestic power supply is its **compatibility with transformers which can reduce power loss**.

Using transformers to reduce power losses

Since electrical power is the product of current and voltage ($P = VI$), the same amount of power can be transmitted using different combinations of current and voltage. For example, a combination of 2.0 A and 10 V provides the same power as 4.0 A and 5.0 V (20 W).
As we have seen earlier in the lesson, the voltage drop $\left(V_{drop} = I_{line}R_{line}\right)$ and the power loss $\left(P_{loss} = I_{line}^2 R_{line}\right)$ both depend on the current. They do not directly depend on the voltage. For this reason, using lower currents (and greater voltages) is preferred for the sake of reducing power loss.

Domestic power could be generated and consumed at a low current and high voltage to reduce power loss, however there are practical reasons (including safety reasons) why lower voltages are preferred. Transformers allow us to change the combination of current and voltage to suit each stage of the transmission system, as shown in Figure 3:

- A **step-up transformer** between the power supply and the transmission lines allows power to be generated at a high current/low voltage and be transmitted at a low current/high voltage.
- A **step-down transformer** between the transmission lines and the load allows power to be transmitted at a low current/high voltage and be consumed at a high current/low voltage.

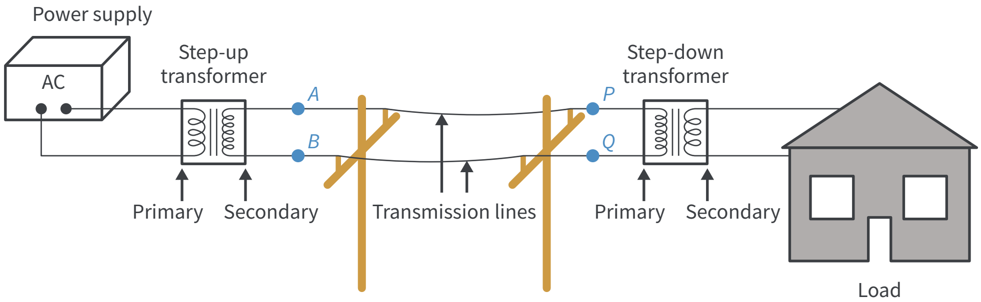


Figure 3 A power transmission with a step-up transformer and a step-down transformer

To analyse a power transmission system involving transformers, it is useful to model the system as a **sequence of sub-circuits** which are separated by the transformers as shown in Figure 4.

- The primary side of each transformer behaves like a load in one sub-circuit.
- The secondary side of the transformer behaves like a power supply in the next sub-circuit.
- The resistance in sub-circuits 1 and 3 is negligible.
- In sub-circuit 2, $V_{PQ} = V_{AB} - V_{drop}$ due to the resistance of the transmission lines.
- The primary and secondary sides of each transformer are related according to the transformer equations covered in lesson 8B $\left(\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}\right)$.

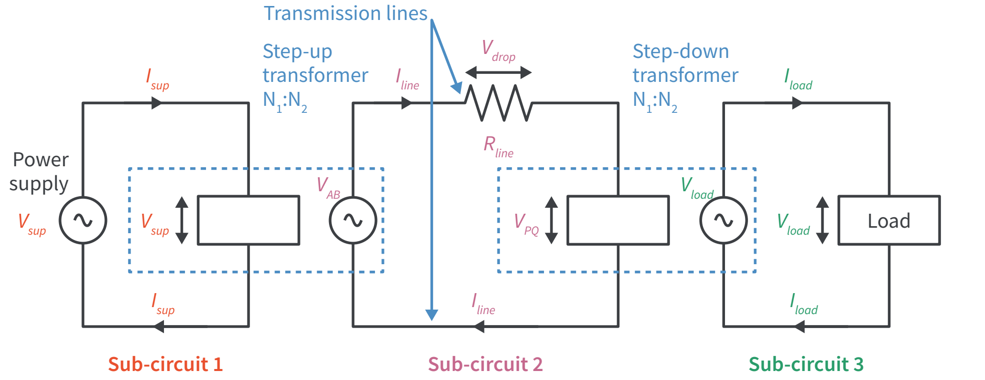


Figure 4 A circuit diagram for the transmission system from Figure 3. Parts of the circuit on either side of a transformer can be modelled as separate series circuits where current/voltage combination in each series circuit is related by the transformer equations.

Depending on the situation, it is not always necessary to use both a step-up transformer and a step-down transformer.

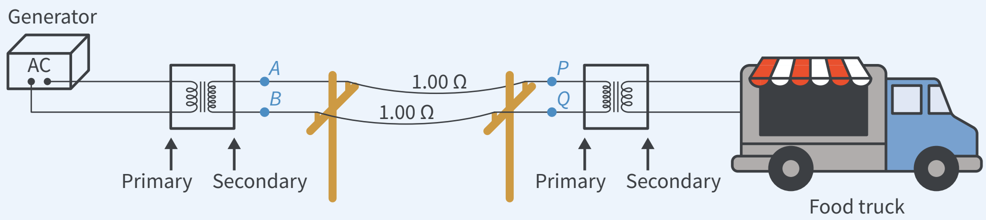
- If there is no step-up transformer, then we can ignore sub-circuit 1 from Figure 4. In this case $V_{AB} = V_{sup}$.
- If there is no step-down transformer, then we can ignore sub-circuit 3 from Figure 4. In this case $V_{PQ} = V_{load}$.

USEFUL TIP

The formulas for power apply only to RMS values, so it is safest to do calculations using RMS and then convert to peak values if needed. Unless the question explicitly asks for a peak value, assume all answers are to be given as RMS values.

2 Worked example

Consider the power transmission system used to supply a food truck from Worked example 1. The same generator (200 W at 40.0 V_{RMS}) is used with the same transmission lines (1.00 Ω each). To reduce power losses the owner installs a step-up transformer with a 1:10 turns ratio between the generator and the transmission lines, and a step-down transformer with a 10:1 turns ratio between the transmission lines and the truck.



a Calculate the current in the transmission lines.

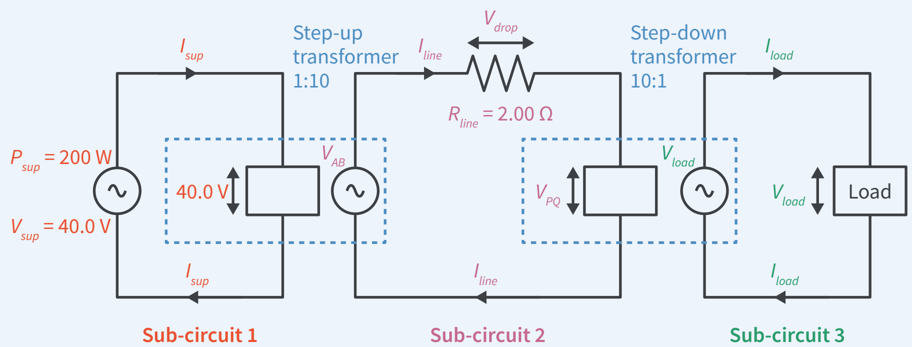
b Calculate the voltage drop across the transmission lines.

c Calculate the power loss in the transmission lines.

d Calculate the voltage delivered to the food truck.

e Calculate the power delivered to the food truck.

The transmission system can be modelled by a circuit diagram as shown.



a Determine the current in sub-circuit 1.

$P_{sup} = V_{sup} I_{sup} \therefore 200 = 40.0 \times I_{sup}$

$I_{sup} = 5.00$ A

Use the transformer ratio for the step-up transformer to determine the current in sub-circuit 2, which is the current in the lines.

$\frac{N_1}{N_2} = \frac{I_{line}}{I_{sup}} \therefore \frac{1}{10} = \frac{I_{line}}{5.00}$

$I_{line} = 0.500$ A

b The voltage drop across the resistance lines depends on the total resistance of the lines.

$R_{line} = 1.00 + 1.00 = 2.00\ \Omega$

$V_{drop} = I_{line} R_{line} = 0.500 \times 2.00 = 1.00$ V

Note that this voltage drop is a factor of 10 less than without the transformers (in Worked example 1).

c $P_{loss} = V_{drop} I_{line} = 1.00 \times 0.500 = 0.500$ W

OR

$P_{loss} = I_{line}^2 R_{line} = 0.500^2 \times 2.00 = 0.500$ W

OR

$P_{loss} = \frac{V_{drop}^2}{R_{line}} = \frac{1.00^2}{2.00} = 0.500$ W

Note that this power loss is a factor of 100 (10^2) less than without the transformers (in Worked example 1).

d Use the transformer ratio for the step-up transformer to determine the voltage output from the transformer in sub-circuit 2, V_{AB}.

$\frac{N_1}{N_2} = \frac{V_{sup}}{V_{AB}} \therefore \frac{1}{10} = \frac{40.0}{V_{AB}}$

$V_{AB} = 400$ V

Determine the voltage on the primary side of the step-down transformer in sub-circuit 2.

$V_{PQ} = V_{AB} - V_{drop} = 400 - 1.00 = 399$ V

Use the transformer ratio for the step-down transformer to determine the voltage output from the transformer in sub-circuit 3 which is the same as the voltage delivered to the food truck, V_{load}.

$\frac{N_1}{N_2} = \frac{V_{PQ}}{V_{load}} \therefore \frac{10}{1} = \frac{399}{V_{load}}$

$V_{load} = 39.9$ V

e $P_{load} = P_{sup} - P_{loss} = 200 - 0.500 = 199.5$ W

OR

$P_{load} = V_{load} I_{load} = 39.9 \times 5.00 = 199.5$ W

To three significant figures, the power delivered to the food truck would be 200 W.

Theory summary

- Simple power transmission systems consist of a power supply, transmission lines, and a load (where the power is intended to be used).
- Transmission lines over long distances have a significant resistance which can lead to significant voltage drop and power loss.
- Transformers are used to transmit power at low current and high voltage which reduces voltage drop and power loss. The power loss will be reduced by a factor which is the square of the factor by which the current decreases $\left(P_{loss} = I_{line}^2 R_{line}\right)$.
- The benefits of transformers apply to AC power. Transformers are not effective in transmission systems which use a constant DC power supply.

8C Questions

THEORY REVIEW QUESTIONS

Question 1

The best reason why AC power is preferred to constant DC power for long distance power transmission is because

A AC power is easier to generate than DC power.

B it is easier to build appliances that use AC power than DC power.

C AC power is faster to transmit that DC power.

D AC power can be transmitted more efficiently than DC power with the use of transformers.

Question 2

A step-up transformer **decreases the current** on its secondary side, which reduces power loss when it is placed between a power supply and transmission lines since $P = I^2R$. A step-up transformer also **increases the voltage** on the secondary side. Given that $P = \frac{V^2}{R}$, which is the best explanation for why the **increase in voltage does not cause an increase in power loss**?

A When calculating power loss using $P = \frac{V^2}{R}$, V represents voltage drop, which decreases since $V_{drop} = I_{line}R_{line}$.

B The formula $P = \frac{V^2}{R}$ does not apply to power loss. It can be used only for power sources.

C The formula $P = \frac{V^2}{R}$ is not applicable when transformers are used.

D To calculate power loss using $P = \frac{V^2}{R}$, the voltage on the primary side of the step-up transformer must be used.

Use the following information to answer Questions 3 and 4.

In an AC power transmission system, a step-up transformer is installed between the power supply and the transmission lines. The transformer has a turns ratio of 1:4.

Question 3

By what factor will the voltage drop across the transmission lines decrease?

A 2

B 4

C 8

D 16

Question 4

By what factor will the power loss in the transmission lines decrease?

A 2

B 4

C 8

D 16

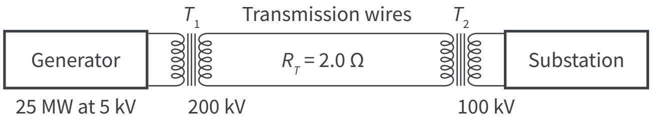
EXAM-STYLE QUESTIONS

This lesson

Question 5 (4 MARKS)

The figure shows a generator at an electrical power station that generates 25 MW_{RMS} of power at 5 kV_{RMS} AC.

Transformer T_1 steps the voltage up to 200 kV_{RMS} AC for transmission through transmission wires that have a total resistance, R_T, of 2.0 Ω. Transformer T_2 steps the voltage down to 100 kV_{RMS} AC at the substation. Assume that both transformers are ideal.



The current in the transmission lines is 125 A.

a Calculate the total electrical power loss, in kilowatts, in the transmission wires. (2 MARKS)

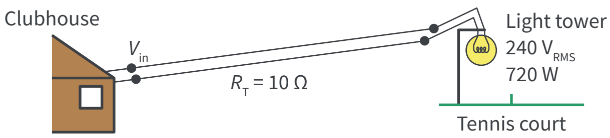
b Transformer T_1 stepped the voltage up to 20 kV_{RMS} AC instead of 200 kV_{RMS} AC. By what factor would the power loss in the transmission lines increase? (2 MARKS)

Adapted from 2017 VCAA Exam Section B Q6

Question 6 (8 MARKS)

A clubhouse power supply operates a 240 V_{RMS}, 720 W light tower at a tennis court. The connecting wires have a total resistance, R_T , of 10 Ω.

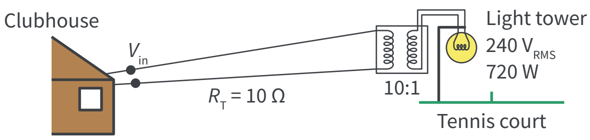
The connecting wires are provided with the required input voltage, V_{in}, at the clubhouse so that the lights operate correctly at 240 V_{RMS} and 720 W.



a When the lights are operating at 240 V_{RMS} and 720 W, what is the power loss in the connecting wires? Show your working. (3 MARKS)

b Calculate the RMS voltage of V_{in}. Show your working. (2 MARKS)

c To reduce the power loss in the connecting wires, an electrician changes the input voltage, V_{in}, and installs a 10:1 step-down transformer near the light tower. After these changes, the lights still operate at 240 V_{RMS} and 720 W.



Calculate the RMS power loss in the connecting wires for this new situation. Show your working. (3 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q4

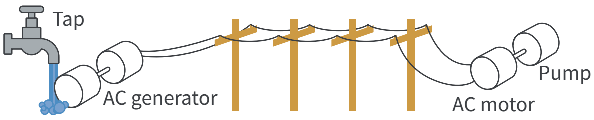
Question 7 (9 MARKS)

Lily and Rose have created a model power transmission system for their practical investigation task in VCE Unit 4 Physics. They use a small AC motor to power a pump. The motor needs 4.0 V_{RMS} AC input for the pump to operate correctly. At this voltage, the motor draws 2.50 A_{RMS}.

a Calculate the power input to the motor when the pump is operating correctly. You may assume that the motor uses power just like a resistor. (1 MARK)

To supply electricity to the AC motor that drives the pump, a small AC generator is used which is driven by the flow of water from a tap. The generator provides current at a voltage of 5.0 V_{RMS} AC.

The connecting wires used to model the transmission lines have a total resistance of 0.80 Ω.



b The motor has a constant resistance of 1.6 Ω.

Calculate the current flowing in the connecting wires. (2 MARKS)

c Determine whether the pump will operate correctly. Justify your answer. (2 MARKS)

d Lily and Rose wish to reduce the power losses in the electrical connections between the AC generator at the tap and the AC motor.

Identify and describe two different changes that would reduce the power losses between the AC generator and the AC motor. In your answer, you must also explain how each of the two changes you identified would reduce power losses. (4 MARKS)

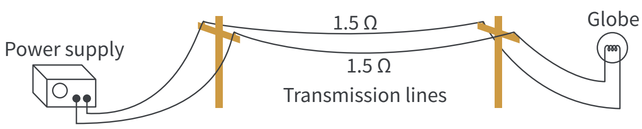
Adapted from 2012 VCAA Exam 2 Section A AoS 1 Q4

Question 8 (15 MARKS)

Willow and Watson are experimenting with a model of a transmission line.

The 'transmission lines' consist of two wires, **each** of constant resistance **1.5 Ω**. As a load they use a 6.0 W globe which operates at 6.0 W when there is 3.0 V across it.

The connecting wires from the power supply to the transmission lines and from the transmission lines to the globe have negligible resistance.



a Initially Willow and Watson use the power supply set on a voltage of 3.0 V DC.

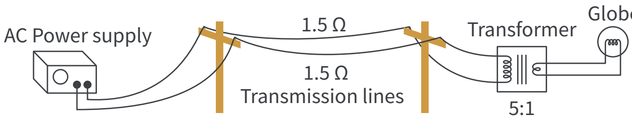
Explain why the globe does not glow as brightly as they expected. (2 MARKS)

b The voltage setting is changed so that the globe operates at 6.0 W as designed. Calculate the required voltage setting of the power supply. (3 MARKS)

c When the globe is operating at 6.0 W as designed, what is the power loss in the transmission lines? (2 MARKS)

Willow says that this power loss is unacceptable. She observes that AC rather than DC is often used for long-distance electric power transmission systems.

d Explain why AC is often used for long-distance electric power transmission. (2 MARKS)



To model this AC transmission system, Willow and Watson modify their experiment by changing the power supply to an (unknown) AC output and using a 5:1 step-down transformer at the other end. The output of the transformer is connected to the globe. The globe is operating at 3.0 V and 6.0 W.

Consider the transformer as ideal.

e What is the power loss in the transmission lines with the new setup? (3 MARKS)

f Calculate the RMS output voltage of the power supply with the new setup. (3 MARKS)

Adapted from 2010 VCAA Exam 2 Section A AoS 1 Q14-20

Previous lessons

Question 9 (3 MARKS)

A person moving parallel to the length of a 4.00 m long space pod observes the change of length of this space pod due to relativity to be 0.040 m.

Calculate the person's speed relative to the space pod in terms of c.

Adapted from 2014 VCAA Exam Section B Detailed study 1 Q3

Question 10 (4 MARKS)

Electrons travelling at 2.5×10^7 m s^{-1} enter a region of uniform magnetic field of strength $B = 8.0 \times 10^{-2}$ T that is at right angles to their path.

a Calculate the magnitude of the force on each electron. (2 MARKS)

b Describe the path of the electrons in this region of uniform magnetic field. Give a reason for your answer. (2 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q1

Key science skills

Question 11 (2 MARKS)

Sonja and Moses are investigating the effect of transformer ratios on power transmission loss using a model power transmission system with a 40 W light globe to represent the load. They progressively increase the transformer ratio and measure the power loss for each value of the ratio. Midway through the investigation the light globe burnt out so they replaced it with a 60 W globe.

Comment on the validity of these results. Justify your answer.

CHAPTER 8 QUESTIONS

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.

Use the following information to answer Questions 1 and 2.

In order to power an electric tool, a farmer must use a step-down transformer that has an input of 240 V_{RMS} AC and an output of 16 V_{RMS} AC. Assume the transformer is ideal.

Question 1

What is the ratio in the numbers of turns in the primary coil compared to the secondary coil (N_1:N_2)?

A 20:1 **B** 15:1 **C** 1:20 **D** 1:15

Question 2

What is the value of the peak current in the transformer's secondary coil? The primary coil delivers 80 W_{RMS}.

A 3.5 A **B** 5.0 A **C** 11 A **D** 7.1 A

Adapted from 2017 VCAA Exam Section A Q4-5

Question 3

The total resistance of a power line is known to be 2.0 Ω. If the power loss in the line is 2450 W, what is the current that flows through the power line?

A 1.2×10^3 A

B 8.2×10^{-4} A

C 35 A

D 2.9×10^{-2} A

Question 4

An ideal transformer has 180 turns on the primary coil and 2880 turns on the secondary coil. The input to the transformer is 60.0 V_{RMS} AC at 60.0 Hz. Which of the following identifies the frequency and peak voltage of the transformer's output?

	Frequency (Hz)	Output (V_{peak})
A	60.0	9.60×10^2
B	60.0	1.36×10^3
C	9.60×10^2	6.79×10^2
D	1.36×10^3	60.0

Question 5

Pendles is stealing power from the government because he thinks it is unfair that they take his tax dollars. His home is deep in the desert. He uses a transmission system with a step-up transformer before the transmission lines and a step-down transformer after the transmission lines. In order to decrease power loss, he proposes some modifications to the transmission lines and their existing transformers.

Which of the following options could be used by Pendles to decrease the power loss in the transmission lines?

A Decrease the number of primary turns in the step-up transformer

B Add a transformer with $N_2 = N_1$

C Increase the current in the transmission wire

D Increase the resistance of the wires

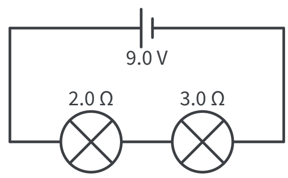
SECTION B

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 9.0 V battery is used to power two light globes in series arranged as shown.



a What is the total resistance of the circuit? (1 MARK)

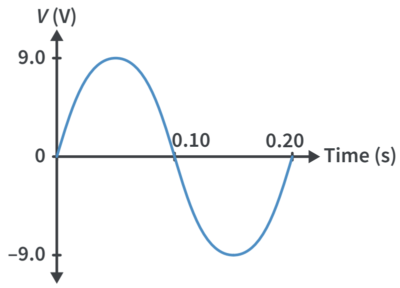
b What is the current within the circuit? (2 MARKS)

c Calculate the voltage drop across the 2.0 Ω resistor. (1 MARK)

d Calculate the power dissipated by the 3.0 Ω resistor. (1 MARK)

Question 7 (3 MARKS)

The graph shows the AC signal produced by an alternator.



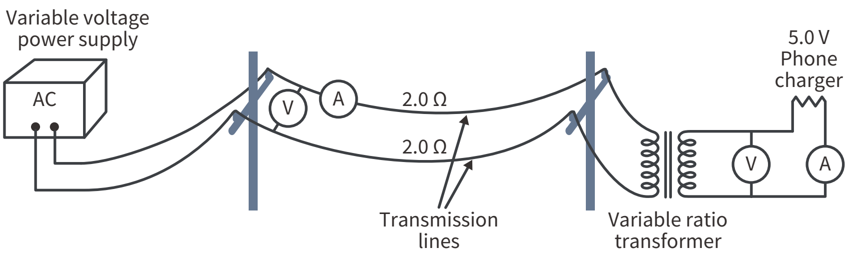
a Calculate the peak-to-peak voltage. (1 MARK)

b Determine the peak voltage. (1 MARK)

c Calculate the root-mean-square voltage. (1 MARK)

Question 8 (10 MARKS)

Coco decides she will try to create her own power transmission system to recharge her phone. She connects two transmission wires of 2.0 Ω (total 4.0 Ω) to an AC power supply, then to a variable step-down transformer, and then to her phone. The variable ratio transformer is set to have a primary to secondary ratio of 3:1 and there is a current of 2.5 A in the transmission wires. With this setup the phone charger correctly operates at 5.0 V_{RMS}.



a What is the total power loss in the transmission wires? (2 MARKS)

b Calculate the power delivered to the phone charger. (2 MARKS)

c What is the power output of the power supply? (2 MARKS)

d Calculate the voltage output of the power supply. (2 MARKS)

e Coco changes the variable transformer so that it now has a ratio of 6:1 and adjusts the power supply so the phone charger operates correctly with 5.0 V_{RMS} across it. Calculate how much power will now be lost in the transmission lines. (2 MARKS)

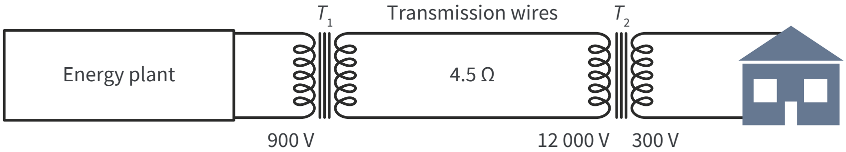
Adapted from 2018 VCAA Exam Section B Q5

Question 9 (3 MARKS)

Explain why AC power is preferred for long-distance power transmission compared to a constant DC power supply.

Question 10 (6 MARKS)

Two transformers, T_1 and T_2 are used when transmitting power from a green energy plant that produces 900 V_{RMS} to a home which requires 300 V_{RMS}. The voltage input at the primary coil of T_2 is 12 000 V_{RMS}. The secondary coil of T_2 has 50 turns. The energy plant produces constant power.



a How many turns are on the primary coil of T_2? (2 MARKS)

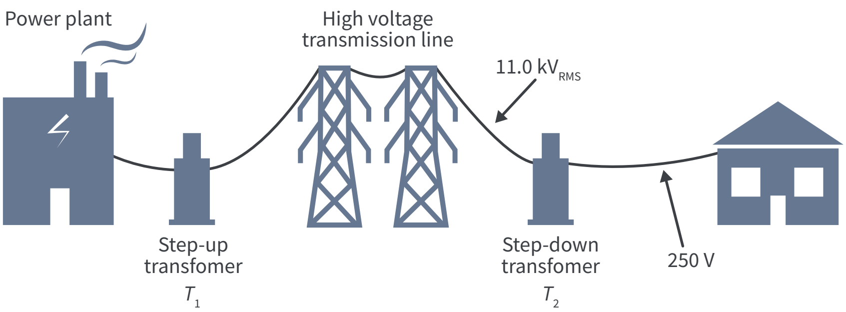
b The ratio of secondary to primary coils in T_1 is doubled. Express the new power loss, $P_{new\ loss}$, as a proportion of the original power loss, $P_{old\ loss}$. Show your working. (2 MARKS)

c Explain why the transformers would be ineffective if the energy plant was replaced with a large DC battery. (2 MARKS)

Adapted from 2017 VCAA Exam Section B Q6

Question 11 (10 MARKS)

The diagram shows the process of transmitting power from a power plant to a house. The step-up transformer has a ratio of primary to secondary turns of 1:40. The transmission line has a resistance of 25.0 Ω. The wires between the power plant and the step-up transformer and between the step-down transformer and the house have negligible resistance. The input to the step-down transformer is 11.0 kV_{RMS}. It has an output of 250 V_{RMS} for use at a house. The house is currently drawing 15.0 kW.



a Calculate the current delivered to the house. (2 MARKS)

b What is the power loss through the transmission lines? (3 MARKS)

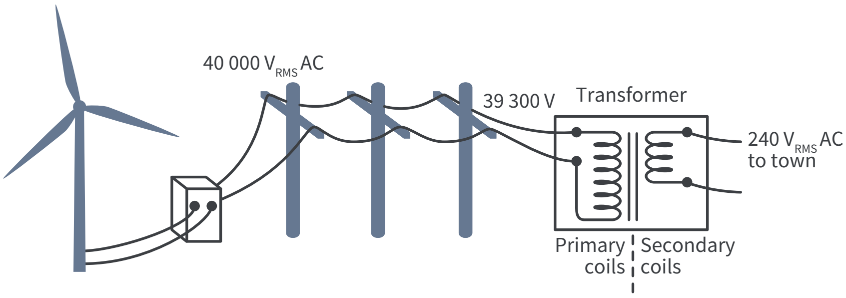
c Find the output voltage of T_1 (the step-up transformer). Give your answer to 4 significant figures. (2 MARKS)

d Given that the step-up transformer has 25 turns in its primary coil, find the number of turns in the secondary coil. (1 MARK)

e Calculate the power output of the power plant. Give your answer to 4 significant figures. (2 MARKS)

Question 12 (5 MARKS)

Jazzy is a young and aspiring electrical engineer with the selfless desire to power her town with Melbourne's Antarctic winds. She builds a wind turbine that produces 40 000 V_{RMS} AC connected to two transmission wires. The wires carry a current of 10.0 A_{RMS} to a transformer in her living room where an input voltage of 39 300 V_{RMS} is converted to 240 V_{RMS}.



a What power does the wind turbine supply to the transmission wires? (1 MARK)

b The power loss in the transmission wires is known to be 7000 W. What is the total resistance of the transmission wires? (2 MARKS)

c Knowing that the transformer Jazzy used is ideal, calculate the ratio of the current in the secondary coils to the current in the primary coils $\left(\frac{I_2}{I_1}\right)$. (2 MARKS)

Adapted from 2011 VCAA Exam 2 Section A AoS 1 Q13

Question 13 (3 MARKS)

A power supply that is producing an AC voltage of 200 V_{RMS} is placed in series with a 100 Ω resistor.

a Calculate the peak value of the voltage. (1 MARK)

b What is the equivalent DC voltage that will provide the same average power? Justify your answer. (2 MARKS)

UNIT 3, AOS 2 QUESTIONS

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

TOTAL MARKS: 50

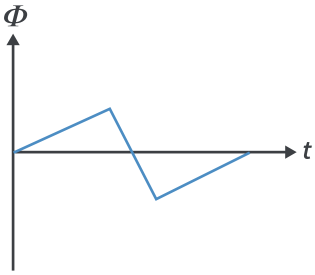
SECTION A

All questions in this section are worth one mark.

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

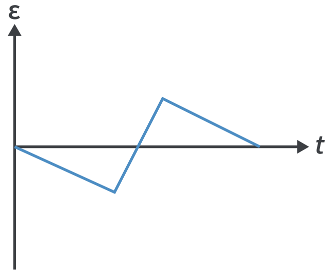
Question 1

The graph shows the magnetic flux passing through a coil of wire over time.

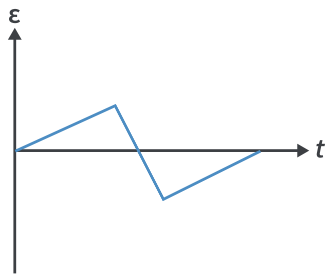


Which of the following graphs could be the resulting EMF induced within the coil of wire?

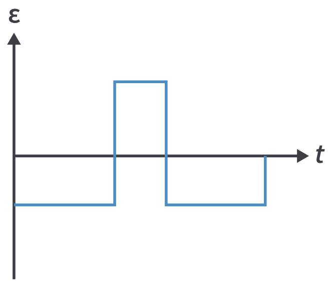
A



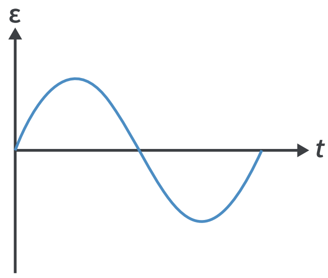
B



C



D



Adapted from 2017 VCAA Exam Section A Q6

Use the following information to answer Questions 2 and 3.

Whilst creating a high voltage electric fence, Nikola uses a step-up transformer that converts 240 V_{RMS} to 6000 V_{RMS}. It is known that the transformer is ideal and that the primary coil delivers 75.0 W_{RMS} to the transformer.

Question 2

What is the ratio of turns in the primary coil compared to the secondary coil in the transformer?

A 1:80

B 1:25

C 25:1

D 80:1

Question 3

What is the peak current in the secondary coil of the transformer?

A 1.25×10^{-2} A

B 1.77×10^{-2} A

C 1.13×10^{2} A

D 8.00×10^{1} A

Adapted from 2017 VCAA Exam Section A Q4-5

Question 4

An AC generator is used to power a machine that requires a voltage of 7.5 V_{RMS}. The generator has 80 turns of wire which, in a quarter of rotation, experience a change in magnetic flux of 2.2 mWb.

For the correct functioning of the machine, what is the period of a quarter rotation of the generator?

A 2.3×10^{-2} s

B 2.3×10^{1} s

C 4.3×10^{-2} s

D 3.3×10^{-2} s

Question 5

In order to increase the output voltage of a DC generator, a manufacturer could

A decrease the period of rotation.

B reduce the area of the coils.

C use slip rings.

D Both A and C.

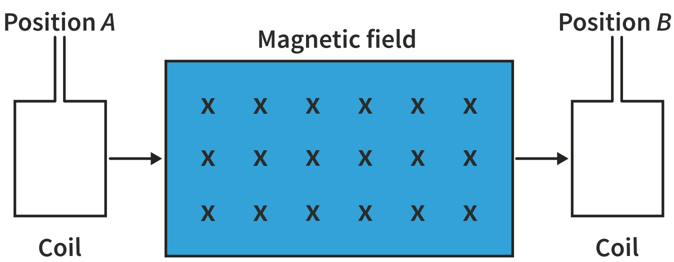
SECTION B

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 (8 MARKS)

A rectangular coil of wire made of 25 loops, measuring 15 cm × 25 cm, is moved back and forth through a magnetic field of 0.500 T at a constant speed. The diagram shows the apparatus as viewed from the north pole of the magnet creating the field.



a Draw a graph that shows the magnetic flux passing through the coil versus time as it moves from position *A* to position *B*, and then back to position *A*. You do not need to include any values. (2 MARKS)

b Draw a graph that shows the induced EMF versus time as the coil moves from position *A* to position *B*, and then back. You do not need to include any values. (2 MARKS)

c If the coil takes 0.10 s to move from completely outside the magnetic field to completely inside, what is the magnitude of the induced EMF in the coil? (2 MARKS)

d As viewed from the north pole of the magnet, determine the direction of the current in the coil as it enters the magnetic field. Justify your answer. (2 MARKS)

Question 7 (6 MARKS)

An AC generator that produces 9.0 V_{RMS} and 3.5 A is used to transport power from a farmer's shed to a home 400 m away. Due to the distance, the farmer decides to install a step-up transformer with a turns ratio of 1:10 immediately after the generator.

a Explain the function of slip rings in an AC alternator and how they work. (2 MARKS)

b If the total resistance of the transmission lines carrying power from the transformer to the farmer's house is 3.5 Ω, what is the power loss in the lines? (2 MARKS)

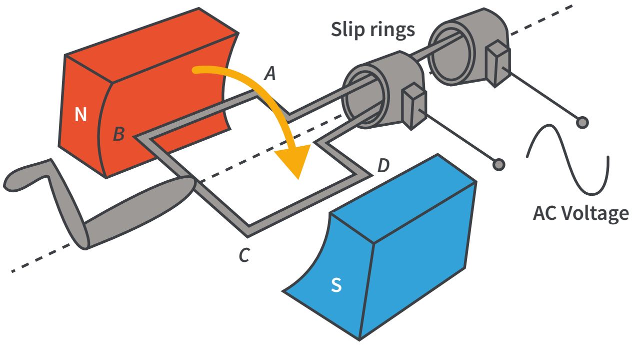
c What change could he make to his generator to produce DC electricity? Explain your answer. (2 MARKS)

Question 8 (2 MARKS)

Explain what would happen if a constant DC current is the input to a step up transformer.

Question 9 (10 MARKS)

Kayla constructs a simple alternator with 10 loops of wire measuring 7.5 cm × 12.5 cm, which rotates 12 times per second. A magnetic flux of 7.5×10^{-3} Wb passes through the coil in the vertical position.



Electrical Generator

a What is the strength of the magnetic field acting on the coil? Include an appropriate unit in your answer. (3 MARKS)

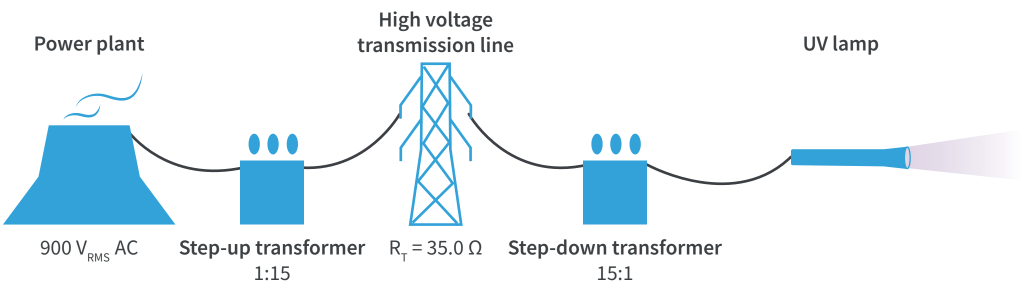
b Find the average EMF induced in the coil over one quarter rotation. (3 MARKS)

c What is the direction of the EMF in the coil over the first quarter rotation? Choose either ***B* to *C*** or ***C* to *B***. Explain your answer. (2 MARKS)

d Kayla gets tired and the rotation of the generator slows at a constant rate. Draw a graph showing how the EMF in the coil changes over time as the rotation slows. Values are not required. (2 MARKS)

Question 10 (7 MARKS)

A sunbaking enthusiast decides to redirect the electricity from their city's transmission line into an experimental UV lamp. They utilise the existing ideal step-up and step-down transformers with ratios of 1:15 and 15:1 respectively. The lamp correctly operates with 890 V across it. The transmission line has a total resistance of 35.0 Ω and carries a current of 16.0 A. The city's power plant produces 900 V_{RMS} AC.



a How much power is lost in the transmission lines? (2 MARKS)

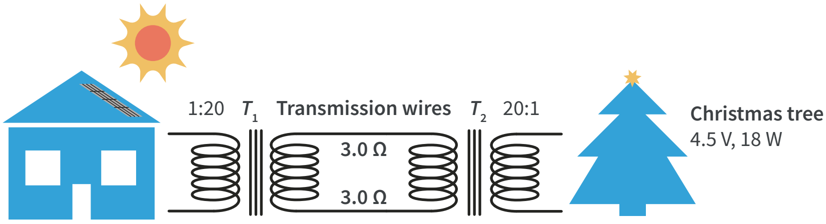
b Determine the voltage across the UV lamp. (4 MARKS)

c The UV lamp does not operate correctly under these conditions. State one change that could be made to the power system so that the lamp correctly operates. (1 MARK)

Adapted from 2018 VCAA NHT Exam Section B Q5

Question 11 (12 MARKS)

In order to power their neighbour's Christmas tree lights, a kind family use their solar panels and an inverter to produce AC power. They position a step-up transformer, T_1, and a step-down transformer, T_2, with ratios of 1:20 and 20:1, respectively, between the solar panels and the Christmas tree. Their goal is to efficiently power the 4.5 V, 18 W Christmas tree lights via two transmission wires with a resistance of 3.0 Ω each.



a If the lights are operating correctly, what is the current in the transmission wires? (3 MARKS)

b Determine the power loss in the transmission wires. (2 MARKS)

c Calculate the voltage input to the step-up transformer required for the lights to function correctly. (4 MARKS)

d Explain why AC is favourable for long-distance power transmission compared to DC. (3 MARKS)

Adapted from 2015 VCAA Exam Section A Q16

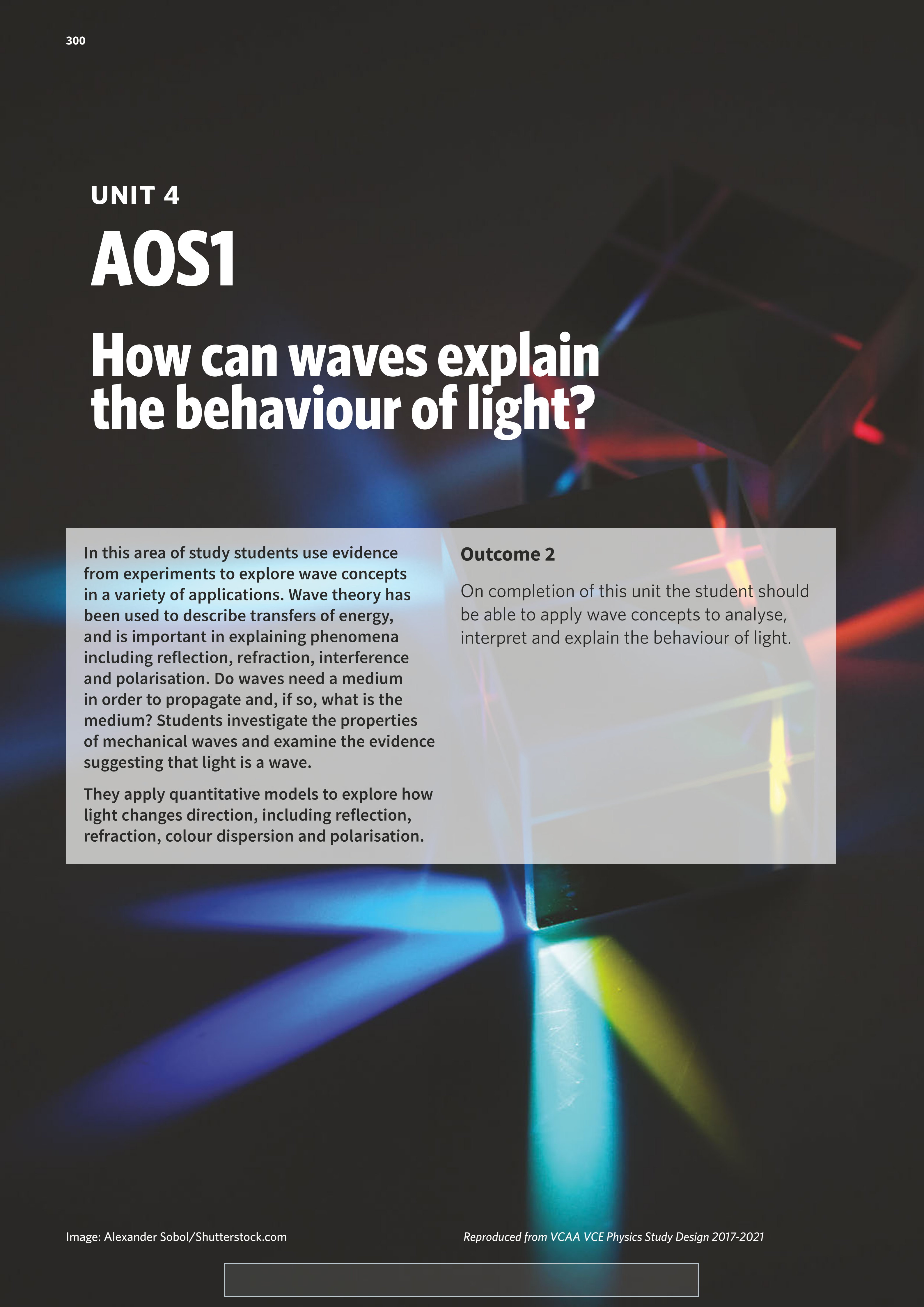
UNIT 4

How can two contradictory models explain both light and matter?

A complex interplay exists between theory and experiment in generating models to explain natural phenomena including light. Wave theory has classically been used to explain phenomena related to light; however, continued exploration of light and matter has revealed the particle-like properties of light. On very small scales, light and matter – which initially seem to be quite different – have been observed as having similar properties. In this unit, students explore the use of wave and particle theories to model the properties of light and matter. They examine how the concept of the wave is used to explain the nature of light and explore its limitations in describing light behaviour.

Students further investigate light by using a particle model to explain its behaviour. A wave model is also used to explain the behaviour of matter which enables students to consider the relationship between light and matter. Students learn to think beyond the concepts experienced in everyday life to study the physical world from a new perspective. Students design and undertake investigations involving at least two continuous independent variables.

Image: lera_virskaya/Shutterstock.com



UNIT 4

AOS1

How can waves explain the behaviour of light?

In this area of study students use evidence from experiments to explore wave concepts in a variety of applications. Wave theory has been used to describe transfers of energy, and is important in explaining phenomena including reflection, refraction, interference and polarisation. Do waves need a medium in order to propagate and, if so, what is the medium? Students investigate the properties of mechanical waves and examine the evidence suggesting that light is a wave.

They apply quantitative models to explore how light changes direction, including reflection, refraction, colour dispersion and polarisation.

Outcome 2

On completion of this unit the student should be able to apply wave concepts to analyse, interpret and explain the behaviour of light.

Image: Alexander Sobol/Shutterstock.com

UNIT 4 AOS 1, CHAPTER 9

Properties of mechanical waves

09

Key knowledge

- explain a wave as the transmission of energy through a medium without the net transfer of matter
- distinguish between transverse and longitudinal waves
- identify the amplitude, wavelength, period and frequency of waves
- calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$
- investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively
- explain qualitatively the Doppler effect
- explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration
- analyse the formation of standing waves in strings fixed at one or both ends
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio

9A WAVE FUNDAMENTALS

This lesson introduces the concept of mechanical waves and distinguishes between transverse and longitudinal waves. It also defines the key properties of waves (amplitude, wavelength, period, and frequency) and explains how to determine these properties from graphs.

This lesson provides the foundation for Unit 4, which examines various forms of waves, and more specifically Area of Study 1, which investigates how light can be modelled as an electromagnetic wave.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot points

- explain a wave as the transmission of energy through a medium without the net transfer of matter
- distinguish between transverse and longitudinal waves
- identify the amplitude, wavelength, period and frequency of waves

Key knowledge units

Wave definition	4.1.1.1
Types of mechanical waves	4.1.2.1
Wave properties	4.1.3.1

Formulas for this lesson

Previous lessons		New formulas
7C	$f = \frac{1}{T}$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

amplitude the magnitude of the maximum oscillation

compression a point in the medium of a longitudinal wave where pressure is maximum

crest a point in the medium of a transverse wave where particles have maximum positive displacement

frequency the number of wave cycles completed per unit of time

longitudinal (compression) wave a wave in which the oscillations are parallel to the direction of wave travel and energy transmission

mechanical wave a wave which requires a material medium

medium the physical substance through which a wave propagates

period the time taken to complete one wave cycle

rarefaction a point in the medium of a longitudinal wave where pressure is minimum

transverse wave a wave in which the oscillations are perpendicular to the direction of wave travel and energy transmission

trough a point in the medium of a transverse wave where particles have maximum negative displacement

wave the transmission of energy via oscillations from one location to another without the net transfer of matter

wave cycle the process of a wave completing one full oscillation, ending up in a final configuration identical to the initial configuration

wavelength the distance between two identical points in a wave

Wave definition 4.1.1.1

OVERVIEW

An understanding of the properties and behaviour of waves is important to be able to understand many aspects of the physical world including sound and light.

THEORY DETAILS

A wave is a transfer of energy without the net transfer of matter. The waves that we will consider in this chapter all propagate (travel) through a medium. These waves are called mechanical waves and are distinct from electromagnetic waves which do not require a material medium.

Examples of mechanical waves include sound waves, which transfer sound energy through air (or another medium), and a ripple in a pond, which transfers kinetic energy through water. In these examples, the air particles and the water particles oscillate (move repetitively) around their respective equilibrium positions; they do not travel with the wave as it propagates.

We can visualise the transfer of energy without the net transfer of matter by imagining a boat floating on smooth ocean waves. The motion of the boat represents the motion of an individual particle in the water below. As the wave moves towards the beach, energy is transferred in that direction. The boat, however, does not move towards the beach; it oscillates up and down.

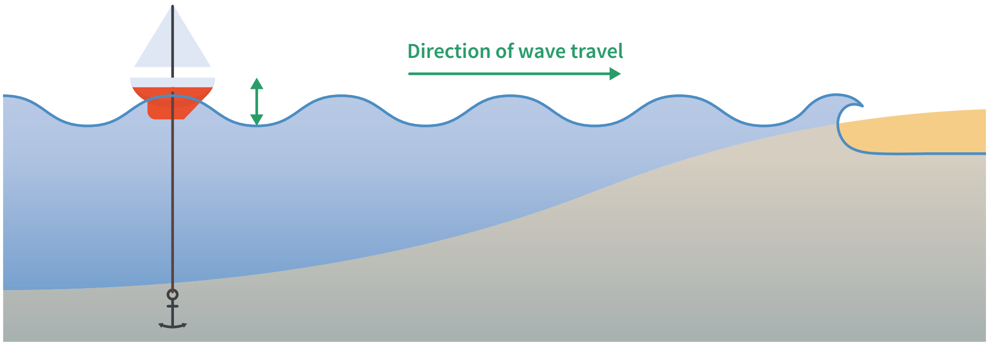


Figure 1 A boat on the water moves up and down as waves pass to the right.

Types of waves 4.1.2.1

OVERVIEW

The types of mechanical waves we will consider in this chapter are transverse waves and longitudinal waves. These can be distinguished by the direction that the particles in the medium oscillate in relation to the direction of wave propagation.

THEORY DETAILS

Transverse waves

The oscillations of particles in a transverse wave are perpendicular to the direction of wave propagation. For example, for a transverse wave travelling to the right, the particles in the medium could oscillate up and down or into and out of the page, but not left and right.

Common examples of transverse waves include waves in strings and water waves.

The points in a medium where particles have maximum positive displacement are called crests. The points where particles have maximum negative displacement are called troughs.

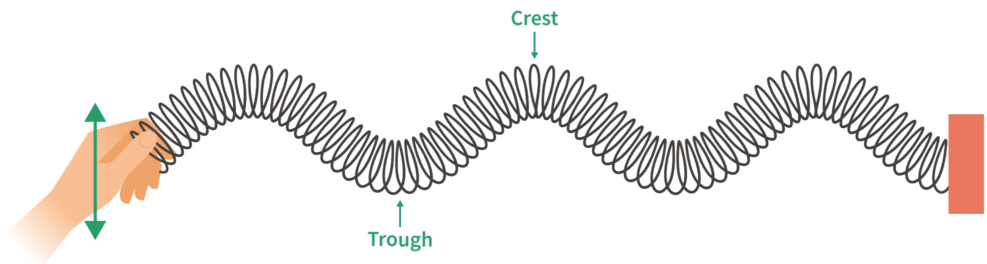


Figure 2 The crest and trough in a transverse wave are shown. The wave travels to the right while the coils in the spring oscillate up and down.

Longitudinal waves

The oscillations of particles in a longitudinal wave are parallel to the direction of wave propagation. For example, for a longitudinal wave travelling to the right, the particles in the medium must oscillate left and right. Longitudinal waves are also commonly referred to as compression waves.

Common examples of longitudinal waves include sound waves, waves in springs, or the primary waves in an earthquake.

The points in a medium where particles are most closely grouped together (under the most pressure) are called compressions. The points where particles are most spread out (under the least pressure) are called rarefactions.

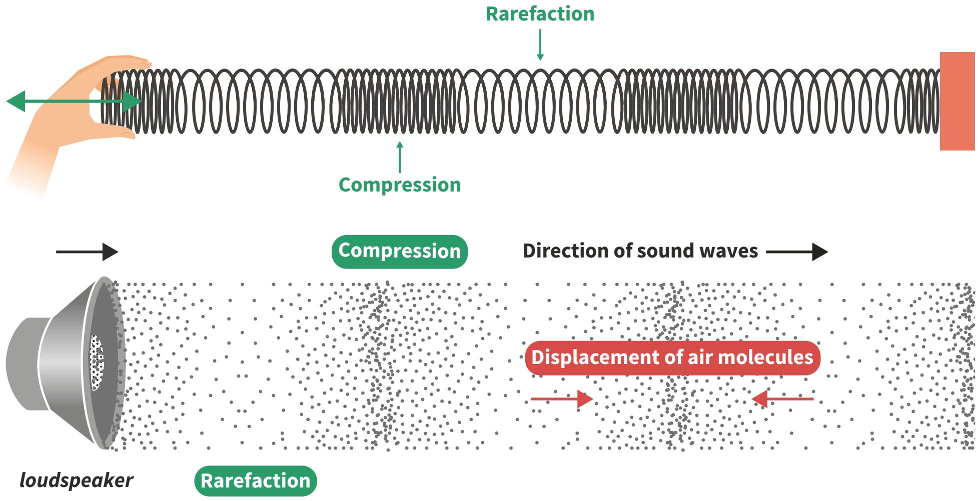


Figure 3 The features of longitudinal waves

Wave properties 4.1.3.1

OVERVIEW

The defining properties of waves are amplitude, wavelength, period and frequency. Graphs are commonly used to represent and identify these properties.

THEORY DETAILS

Amplitude (*A*)

The amplitude of a wave is the magnitude of the maximum oscillation from the equilibrium position. The energy of a wave is dependent on its amplitude. For sound, the amplitude of the wave determines the volume. The unit when determining amplitude from a graph will be the unit of the vertical axis. In the majority of cases we will consider, the SI unit for amplitude is metres (m). If considering a graph with pressure on the vertical axis (often used for sound waves), the units of amplitude will be pressure units.

Wavelength (λ)

The wavelength is the distance between any two identical points in the wave (e.g. the distance from one crest to the next crest). The SI unit for wavelength is metres (m).

Period (*T*)

The period of a wave is the time taken to complete one wave cycle. That is the time for any point on the wave to travel one wavelength. The SI unit for period is seconds (s).

Frequency (*f*)

The frequency of a wave is the number of wave cycles completed per unit of time. That is the number of wavelengths that pass a specific point per unit of time. For sound, increasing frequency corresponds to increasing pitch. The SI unit for frequency is hertz (Hz) which is equivalent to "per second" (s^{-1}).

Frequency and period are related by the following formula.

$$f = \frac{1}{T}$$

Graphing waves

The properties of a wave can be identified from graphs. In particular, it is common to represent waves with graphs that have displacement on the vertical axis and either distance or time on the horizontal axis. Each of these graphs often have a sinusoidal shape.

- Displacement-distance graphs plot the displacement of every point along a wave at one instant. The horizontal axis represents the distance of a point from the wave source.
- Displacement-time graphs plot the displacement of one specific point in the medium as the wave passes through it over time.

When longitudinal waves are represented with displacement on the vertical axis, positive displacement conventionally refers to displacement of the particle in the direction of wave travel.

It is also common to see sound waves represented on graphs with pressure as the vertical axis instead of displacement. The process for identifying wave properties on pressure graphs is exactly the same as for graphs with displacement on the vertical axis, except amplitude is measured in units of pressure.

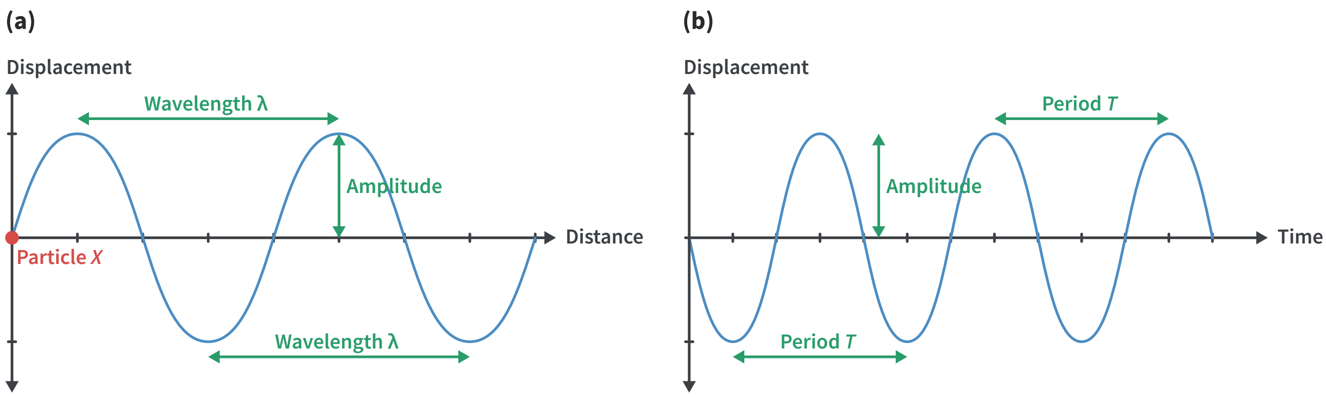
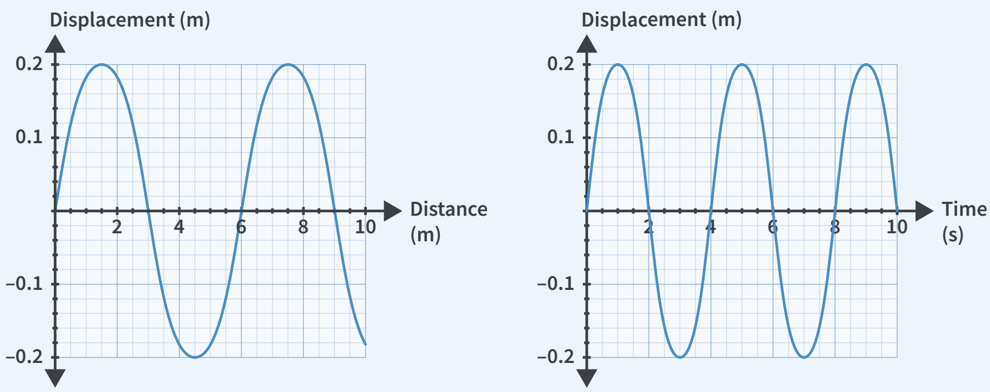


Figure 4 A displacement-distance graph **(a)** shows the position of all the particles in a wave at one instant. The displacement-time graph **(b)** represents the motion of particle *X* over time as the wave propagates through the particle to the right.

1 Worked example



Use the displacement-time and displacement-distance graphs to answer the following:

a **Determine the amplitude.**

b **Determine the wavelength.**

c **Determine the period.**

d **Calculate the frequency.**

a From either graph, the amplitude is 0.2 m

b Using the displacement-distance graph, the wavelength is 6 m

c Using the displacement-time graph, the period is 4 s

d $f = \frac{1}{T} = \frac{1}{4} = 0.25$ Hz

Theory summary

Mechanical waves are the transmission of energy through a medium without the net transfer of matter. There are two types of waves – longitudinal and transverse – which can be distinguished by the direction of their oscillations compared to the direction of wave propagation. The properties of a wave can be found from graphs as summarised in the following table.

Graph type	Amplitude	Wavelength	Period	Frequency
Displacement-distance	✓	✓	✗	✗
Displacement-time	✓	✗	✓	✓ Using $f=\frac{1}{T}$

KEEN TO INVESTIGATE?

oPhysics 'Longitudinal and transverse wave basics' simulation
https://ophysics.com/w6.html

PhET 'Wave on a string' simulation
https://phet.colorado.edu/en/simulation/wave-on-a-string

9A Questions

THEORY REVIEW QUESTIONS

Question 1

A mechanical wave can be best described as

A the transmission of matter through a medium without the net transfer of energy.

B the transmission of alternating electric and magnetic fields without the net transfer of matter.

C the transmission of energy through a medium without the net transfer of matter.

D the transmission of energy through a vacuum without the net transfer of matter.

Question 2

Which of the following is an example of a longitudinal wave?

A A horizontal spring undergoing vertical oscillations

B A violin string being plucked

C A sound from a speaker playing a song through the air

D A water ripple

Question 3

Which of the following is an example of a transverse wave?

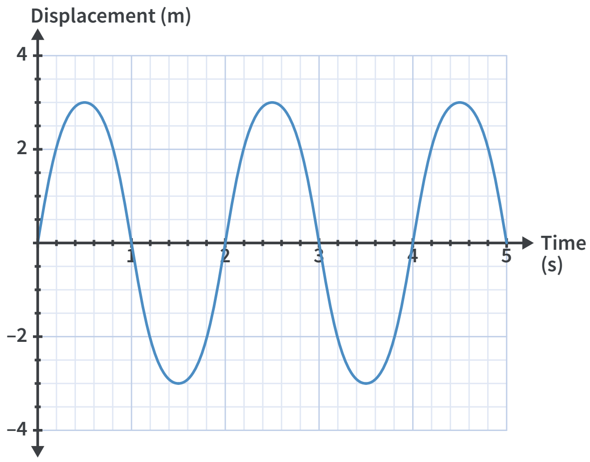
A A horizontal spring undergoing horizontal oscillations

B The air when a singer sings a note

C A whale song through water

D A wave on the surface of the ocean

Use the following information to answer Questions 4–6.



Question 4

What is the amplitude?

A 2 m

B 3 m

C 4 m

D Unable to be determined from this graph

Question 5

What is the wavelength?

A 2 m

B 3 m

C 4 m

D Unable to be determined from this graph

Question 6

What is the period?

A 2 s

B 3 s

C 4 s

D Unable to be determined from this graph

Question 7

If a wave has a period of 0.2 seconds, what is the frequency of the wave?

A 0.2 Hz

B 2 Hz

C 5 Hz

D 50 Hz

Question 8

A tap is dripping into a full bathtub. A drop of water falls every 0.25 seconds, creating a circular ripple when it hits the otherwise still bath water. The wavelength of the ripples (measured crest to crest) is 3.0 cm. What is the frequency of the water drops hitting the bath water?

A 0.25 Hz

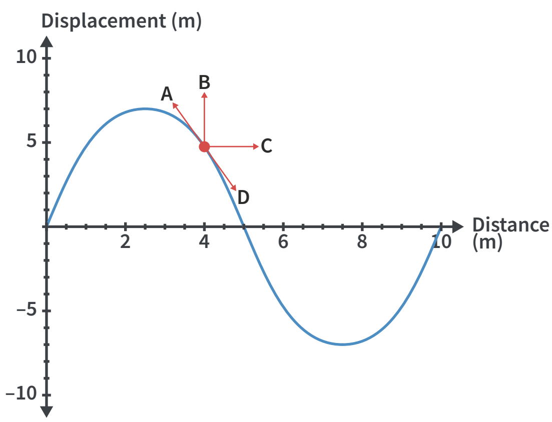
B 0.75 Hz

C 4.0 Hz

D 12 Hz

Question 9

The wave represented in the graph below is moving to the right. In which direction does the particle move at the instant shown: A, B, C or D?

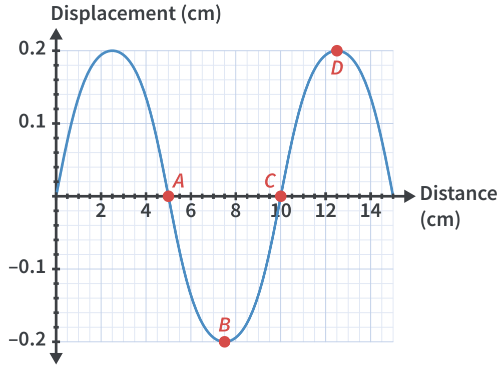


EXAM-STYLE QUESTIONS

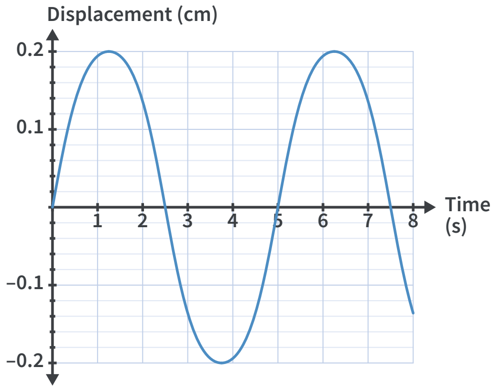
This lesson

Question 10 (5 MARKS)

The following graph shows the displacement of air in front of a speaker at a time $t = 0$ s. The sound wave is moving to the right (increasing distance). Four air particles are indicated on the graph below.



A displacement-time graph of one of the particles during the first 8 seconds of the sound is shown below.



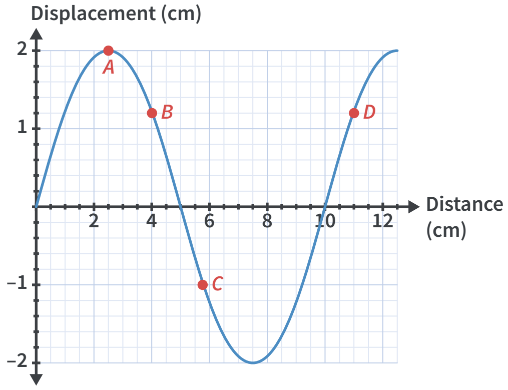
a For which particle (*A*, *B*, *C*, or *D*) is this a displacement-time graph? (1 MARK)

b What is the period and frequency of the sound? (2 MARKS)

c After the first 8 seconds, at what time will the particle next have a displacement of −0.2 cm? (2 MARKS)

Question 11 (6 MARKS)

The following graph relates to a transverse wave in a string that is moving to the right. The displacement is vertical.

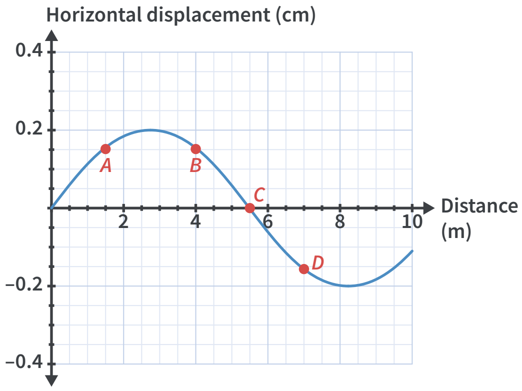


a In what direction (up, down, left, right) are the particles located at positions *A*, *B*, *C* and *D* moving at the instant shown? If a particle is not moving, write 'not moving'. (4 MARKS)

b What will be the distance and displacement of particle *A* after another half period has passed? (2 MARKS)

Question 12 (6 MARKS)

The following graph relates to a longitudinal wave that is moving horizontally to the right. Take displacement to the right as positive.



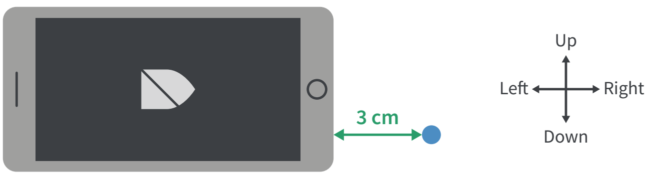
a In what direction (up, down, left, right) are the particles located at positions *A*, *B*, *C*, and *D* moving at the instant shown? If a particle is not moving, write 'not moving'. (4 MARKS)

b What was the distance and displacement of particle *C* one quarter period before this graph was recorded? (2 MARKS)

Question 13 (2 MARKS)

Finn begins playing music out loud from his phone. The air particle shown starts initially at rest 3 cm away from the phone speaker. Finn's music has a frequency of 50 Hz.

The speed of sound is 340 m s^{-1}. Describe the resulting motion of this air particle in relation to its initial position.



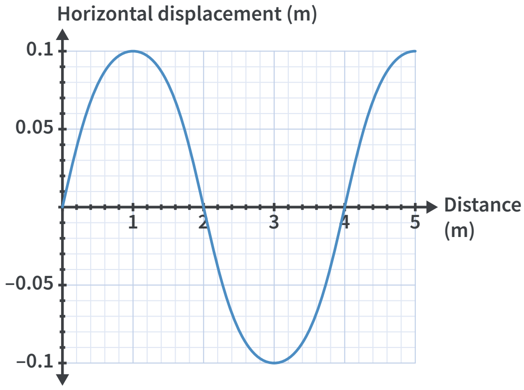
Question 14 (2 MARKS)

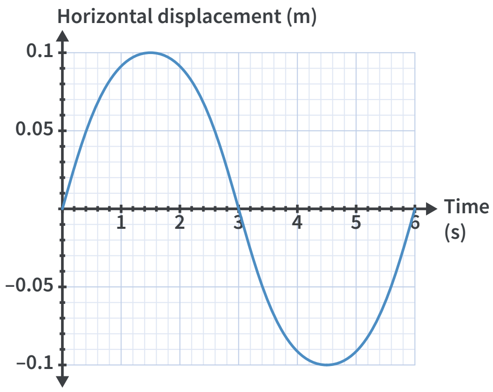
Dominique is singing a note with a period of 0.005 seconds. She finds that the note is flat (the frequency is too low).

Explain whether she should make the period of the note longer or shorter to correct her pitch.

Question 15 (8 MARKS)

The two graphs that follow were generated from a longitudinal wave in a spring that is travelling horizontally to the right. Take displacement to the right as positive.





a Which graph relates to the whole spring, and which specifically relates to one point of the spring? (1 MARK)

b What is the amplitude of the wave? (1 MARK)

c What is the wavelength of the wave? (1 MARK)

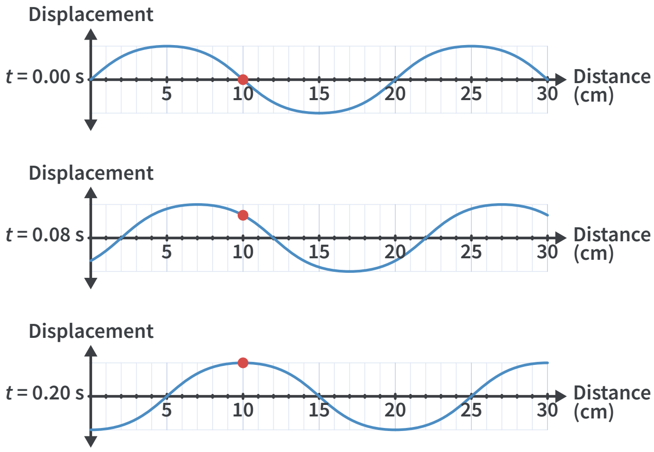
d What is the period of the wave? (1 MARK)

e What is the frequency of the wave? (1 MARK)

f Draw a version of the displacement-distance graph one quarter of a period later. (3 MARKS)

Question 16 (3 MARKS)

The following graphs show the displacement of a point a distance of 10 cm from the end of an oscillating string at three different times.



a What is the wavelength of the wave in the string? (1 MARK)

b What is the lowest possible frequency for the wave in the string? (2 MARKS)

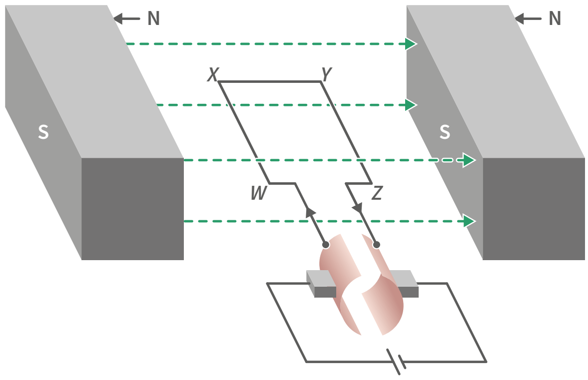
Previous lessons

Question 17 (3 MARKS)

Humanity is expanding throughout the universe to nearby potentially habitable planets. One spaceship of cosmic explorers is voyaging to Proxima Centauri b, a planet 4.01×10^{16} m away from Earth. The spaceship can travel at $0.90c$. Calculate the time, in years, that the astronauts will measure the journey to take.

Question 18 (3 MARKS)

A DC motor is set up using permanent magnets and a split ring commutator. Before the motor is switched on, the coil of the motor is stationary and horizontal (as in the diagram). Explain why the coil begins to rotate when the motor is turned on.



Adapted from 2014 VCAA Exam Section A Q17c

Key science skills

Question 19 (3 MARKS)

Izzy and Emma are using a technique called interferometry to each take 5 repeated measurements of the wavelength of a laser that has an actual wavelength of 695 nm.

Izzy takes the following measurements: 690 nm, 697 nm, 693 nm, 694 nm, 707 nm.

Emma takes the following measurements: 697 nm, 698 nm, 694 nm, 699 nm, 696 nm.

Identify and explain which set of results is more accurate and which set is more precise.

9B WAVE SPEED

This lesson builds on the fundamental properties of waves which were established in the previous lesson to introduce wave speed. It will explain how wave speed relates to wavelength, frequency, and period via the wave equation without being dependent on those properties. This relationship will be used in much of Unit 4.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$

Key knowledge units

Wave speed	4.1.4.1
Wave equation	4.1.4.2

Formulas for this lesson

Previous lessons		New formulas
7C	$f = \frac{1}{T}$	* $v = f\lambda$
		$v = \frac{\lambda}{T}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

wave speed the speed at which a wave propagates through a medium

Wave speed 4.1.4.1

OVERVIEW

Every wave propagates at a certain speed. This knowledge unit will cover the dependence of wave speed on the physical medium through which the wave is propagating.

THEORY DETAILS

Lesson 9A explained that waves are a transfer of energy through a medium. The wave speed is the speed at which the wave transfers its energy through the medium. That is, it is the speed at which the crests and troughs, or compressions and rarefactions, move through the medium. Wave speed is not the speed of the individual oscillating particles in the wave. Wave speed is determined only by the physical properties of the medium in which it travels (e.g. material, density, and temperature). For mechanical waves, it does not depend on the frequency, wavelength, period, or amplitude of the wave.

Consider sound waves as an example. The speed of sound in air is approximately 340 m s^{-1}. This value remains constant for all frequencies and amplitudes (i.e. volumes) of sound.

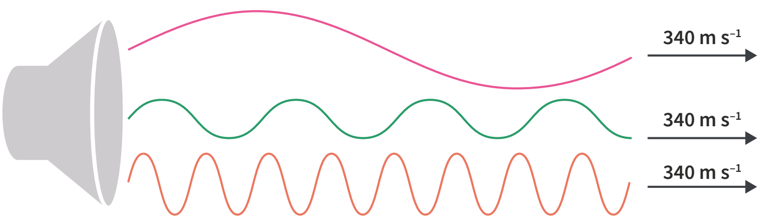


Figure 1 Sound waves being produced by a speaker travel at the same speed in air regardless of frequency, amplitude, or wavelength.

Additionally, sound waves travel at different speeds through different media due to differences in the physical properties of the media. For example, sound travels at 260 m s^{-1} in carbon dioxide, 340 m s^{-1} in air, 1482 m s^{-1} in water, and 5960 m s^{-1} in steel.

Wave equation 4.1.4.2

OVERVIEW

The wave equation is a formulaic representation of the relationship between wave speed, period or frequency, and wavelength.

THEORY DETAILS

Wavelength (λ) measures the distance of one wave cycle, and period (T) measures the time it takes to complete one wave cycle. By applying these properties to the familiar formula, $speed = \frac{distance}{time}$, a version of the wave equation is formed:

$$v = \frac{\lambda}{T}$$

v = wave speed (m s^{-1}), λ = wavelength (m), T = wave period (s)

Given $f = \frac{1}{T}$, the wave equation also takes the following form:

$$v = f\lambda$$

v = wave speed (m s^{-1}), f = frequency (Hz), λ = wavelength (m)

If the frequency is changed, for example, the wavelength will also change such that the speed remains constant in a given medium so the following proportionalities can be derived:

- $\lambda \propto \frac{1}{f}$
- $\lambda \propto T$

1 **Worked example**

A wave of frequency 48 Hz is travelling along a string at a speed of 24 m s^{-1}. What is the wavelength?

$v = f\lambda$

$24 = 48 \times \lambda$

$\lambda = \frac{24}{48} = 0.50$ m

Theory summary

Wave speed is defined as the speed at which a wave propagates through a medium. This speed is determined by the physical properties of the medium and is independent of wave properties even though it does relate to the properties of the wave by the wave equation.

KEEN TO INVESTIGATE?

PhET 'Wave on a string' simulation
https://phet.colorado.edu/en/simulation/wave-on-a-string

9B Questions

THEORY REVIEW QUESTIONS

Question 1

The speed of a wave is determined by

A the wave frequency.

B the disturbance that caused the wave.

C the medium in which the wave travels.

D the period of the wave.

Question 2

The frequency of a wave in a given medium is

A inversely proportional to the wavelength.

B proportional to the wavelength.

C proportional to the square of the wavelength.

D not related to the wavelength.

Question 3

A student is creating waves that propagate along a rope, and wants to alter the speed at which the waves travel. What could the student do to change the wave speed?

A Change the frequency of wave generation.

B Use a rope with different physical properties.

C Change the period of wave generation.

D Increase the amplitude of the waves.

Question 4

A car sounding its horn is travelling at 30 m s^{-1}. What is the speed of the sound waves produced by the horn? Assume the speed of sound in air is 340 m s^{-1}.

A 355 m s^{-1}

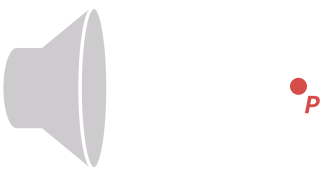
B 370 m s^{-1}

C 310 m s^{-1}

D 340 m s^{-1}

Question 5

A speaker is emitting waves at 220 Hz into air. The waves move at the speed of sound, 340 m s^{-1}, and have a wavelength of 1.55 m. Which option best describes the motion of an air particle at point *P*?



A The air particle oscillates horizontally 220 times a second.

B The air particle oscillates vertically 220 times a second.

C The air particle moves horizontally away from the speaker at 340 m s^{-1}.

D The air particle moves 1.55 m to the right.

Question 6

Which of the following will occur when the frequency of a wave is doubled?

A The amplitude will double.

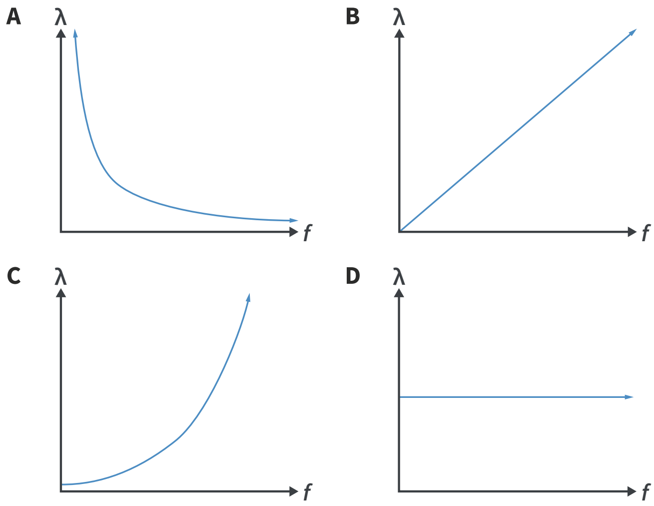
B The speed will double.

C The wavelength will halve.

D The period will double.

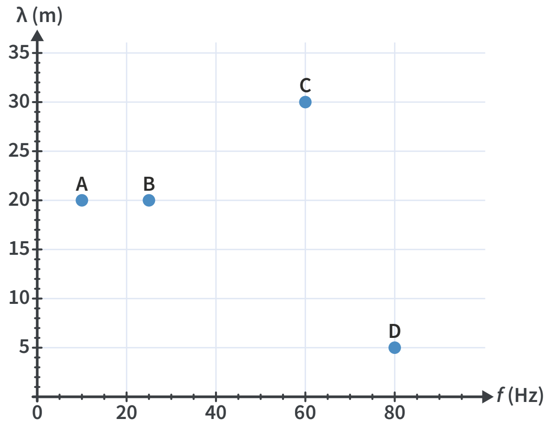
Question 7

Choose the graph that best represents the relationship between wave frequency and wavelength for a wave travelling in constant medium.



Question 8

A student spends their lunchtime recording the frequency and wavelength of various waves found around the school campus and presents the data in a graph. Which of the four waves has the greatest speed?



EXAM-STYLE QUESTIONS

This lesson

Question 9 (2 MARKS)

Sound waves originating in air enter a large tank of water before emerging into the air on the other side. How does the speed of the sound waves before and after the tank compare? Why?

Question 10 (2 MARKS)

A student doubles the period of waves he is producing on a string. What is the effect on the wavelength? Use an equation to support your answer.

Question 11 (1 MARK)

A set of speakers at a school assembly are driving sound waves at a frequency of 135 Hz. Calculate the resulting wavelength, assuming the speed of sound in air is 340 m s^{-1}.

Question 12 (1 MARK)

Timmy is playing the trumpet and produces sound waves with a frequency of 440 Hz that travel at 340 m s^{-1}. What is the wavelength of the sound waves produced by the trumpet?

Question 13 (1 MARK)

A student records the wavelength and frequency of sound waves emitted by a speaker to experimentally determine the speed of sound in air. He records a frequency of 1000 Hz and a wavelength of 0.338 m. What is his experimental value for the speed of sound in air?

Question 14 (1 MARK)

A bodybuilder is creating waves along exercise ropes. The waves exhibit a period of 2.00 s and a wavelength of 4.50 m. At what speed do waves propagate along these ropes?

Question 15 (2 MARKS)

Given the wave equation, $v = f\lambda$, explain why increasing wave frequency does not increase wave speed.

Question 16 (4 MARKS)

a Waves are being generated along the length of a string with a frequency of 10 Hz and a wavelength of 0.25 m. The frequency of the waves changes to 15 Hz. What is the wavelength of the new waves? (2 MARKS)

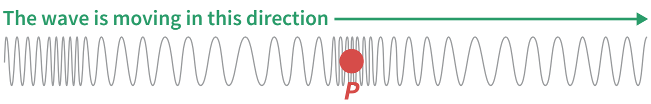
b A student is creating waves on a string, and finds the time and distance between successive wave crests to be 2.0 s and 0.25 m, respectively. The student then generates waves that complete 2.0 cycles per second. What is the wavelength of the new waves? (2 MARKS)

Question 17 (1 MARK)

A wave with $\lambda = 2.0$ cm is travelling along a guitar string. Waves on this particular string have a speed of 70 m s^{-1}. Calculate the frequency of the wave.

Question 18 (2 MARKS)

A longitudinal wave is travelling along a slinky with a period of 8.0 s and speed of 0.40 m s^{-1}.

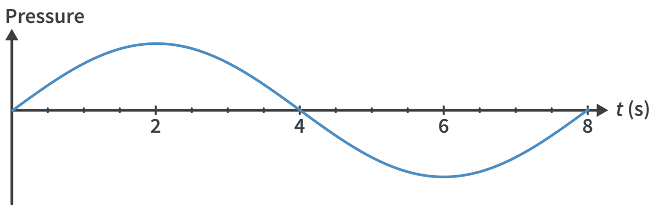


a Determine the wavelength of the slinky wave. (1 MARK)

b Draw an arrow(s) showing the direction of movement over time of a slinky ring at point *P*. (1 MARK)

Question 19 (2 MARKS)

The graph shows the variation in pressure over time of a single point as sound waves pass. Calculate the wavelength of these sound waves to two significant figures. Assume the speed of sound in this medium is 330 m s^{-1}.



Question 20 (2 MARKS)

A cruise ship's instruments determine the time between wave crests of a tsunami with $\lambda = 500$ km is 20.0 minutes. Calculate:

a the frequency of the tsunami. (1 MARK)

b the speed at which it is travelling. (1 MARK)

Question 21 (1 MARK)

The highest frequency of sound waves produced by an animal are emitted by a rare species of katydid, reaching 30 kHz. Assuming the speed of sound in air is 340 m s^{-1}, calculate the wavelength, in millimetres, of these waves.

Question 22 (2 MARKS)

A pair of headphones can emit sound waves between 85 Hz and 18 kHz. What is the longest possible wavelength produced by the headphones? Assume the speed of sound in air is 340 m s^{-1}.

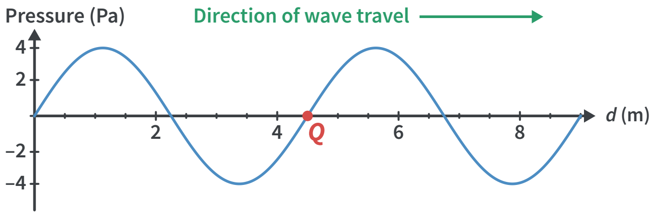
Question 23 (2 MARKS)

A student is using waves to determine the identity of an unknown gas. Waves inside the 2.00 m tube of gas are measured to have a frequency of 534 Hz and a wavelength one quarter of the tube length. What is the unknown gas in the tube?

Gas	Speed of sound (m s^{-1})
Helium	1007
Krypton	221
Hydrogen	1270
Nitrogen	349
Oxygen	326
Carbon dioxide	267

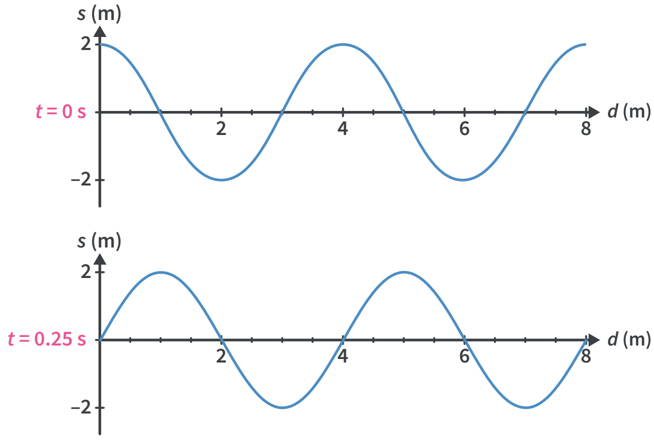
Question 24 (3 MARKS)

The graph shows the deviation in pressure against distance at $t = 0$ s for a wave travelling at 3 m s^{-1}. Sketch a pressure-time graph to show how the pressure at point *Q* varies over time from $t = 0$ s to $t = 6$ s.



Question 25 (4 MARKS)

The two displacement-distance graphs represent a single mechanical wave at two times.



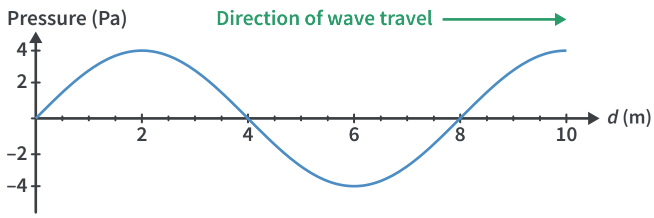
a Determine the wavelength of this wave. (1 MARK)

b What is the lowest possible frequency of the wave? (2 MARKS)

c What is the speed of the wave based on this frequency? (1 MARK)

Question 26 (4 MARKS)

The graph shows the deviation in pressure against distance of a wave travelling at 2 m s^{-1}.



a What is the wavelength of the wave? (1 MARK)

b What is the period of the wave? (1 MARK)

c Sketch a pressure-distance graph of the same wave 2 s after the initial graph. (2 MARKS)

Previous lessons

Question 27 (2 MARKS)

The length of an asteroid is measured to be one quarter of its rest length as it passes a space station. What is the speed of the asteroid determined by the space station? Give your answer as a proportion of *c* to three significant figures.

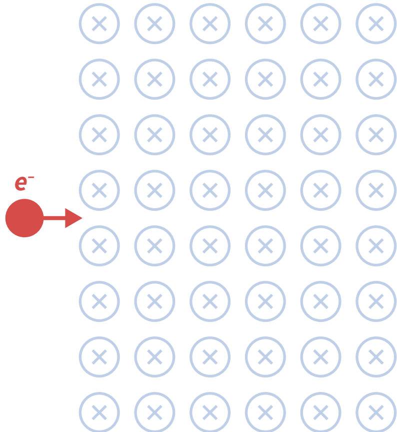
Question 28 (5 MARKS)

Electrons are accelerated from rest between two charged plates in an arm of a particle accelerator. The final speed of the electrons is 5.0×10^7 m s^{-1}.

a What is the potential difference between the plates? Ignore relativistic effects. (2 MARKS)

b The electrons then pass through a perpendicular magnetic field of strength 350 T. What is the radius of curvature of the electrons? (2 MARKS)

c Sketch the path of electrons moving through the magnetic field in the diagram. (1 MARK)



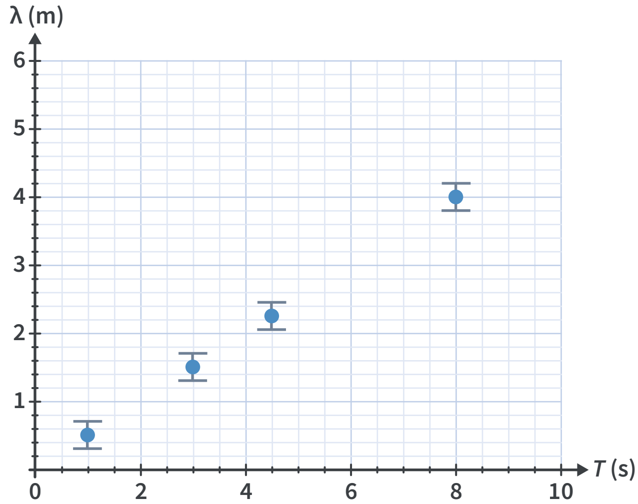
Key science skills

Question 29 (1 MARK)

A student is measuring wave frequency with an oscilloscope. The smallest measurement increment on the oscilloscope is 10 Hz. What is the uncertainty of the oscilloscope?

Question 30 (2 MARKS)

Four measurements of period and wavelength are graphed. From this graph, determine the speed of waves in this medium to two significant figures.



Question 31 (3 MARKS)

Morgan conducted an experiment where she gradually increased the frequency of a wave and measured the resulting wavelength. She recorded four measurements. Plot these measurements on a suitable graph, including uncertainty bars, and draw an appropriate curve of best fit. Note that the frequency was recorded to a high level of confidence.

Frequency (Hz)	Wavelength (m)	Smallest increment of wavelength measuring device (m)
25	2.5	0.5
45	1.5	0.5
60	1.0	0.5
110	0.5	0.5

9C THE DOPPLER EFFECT

Have you ever noticed how the pitch of a police siren or a car horn seems to change when the vehicle passes you? This is known as the Doppler effect.

This lesson will investigate motion in a wave medium and how the Doppler effect arises from such motion.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- explain qualitatively the Doppler effect

Key knowledge units

Motion in a medium	4.1.6.1
The Doppler effect	4.1.6.2

Formulas for this lesson

Previous lessons		New formulas
9B	* $v = f\lambda$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

Doppler effect the detected frequency change due to the relative motion between a wave source and detector

Motion in a medium 4.1.6.1

OVERVIEW

The movement of a wave source and/or detector relative to the wave medium has an effect on the properties of the waves observed.

THEORY DETAILS

In any system where waves are observed, there is a wave source (e.g. speaker, tap dripping) and a wave detector (e.g. microphone, human ear). The motion of either the source or detector relative to the medium they are in will modify the properties of the waves created or observed.

Consider a tap dripping (the source) regularly into a pool of water. Waves propagate out at a constant frequency in all directions from the source as in Figure 1.

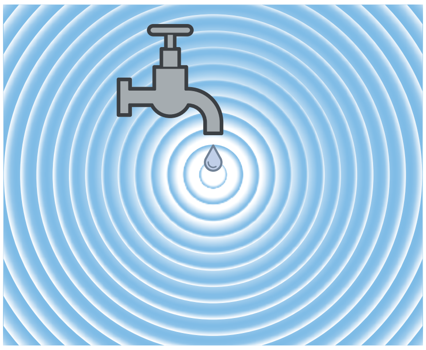


Image: GeoArt/Shutterstock.com

Figure 1 Waves created by a stationary source

Moving source

Now consider the case where the source is moving through the medium. As the source moves, it chases the wave crests in front of it and moves further away from wave crests behind it. This causes waves in front of the source to bunch up (decrease wavelength) while waves behind the source spread apart (increase wavelength) as in Figure 2.

Waves **in front of a moving source** have a shortened wavelength and **increased frequency**. Waves **behind a moving source** have a lengthened wavelength and **decreased frequency**.

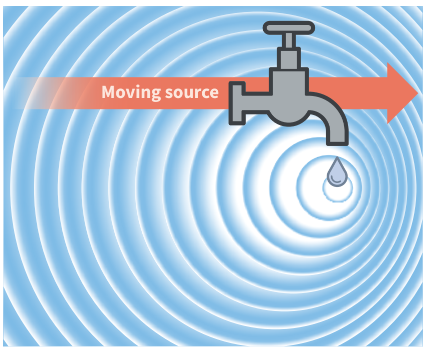


Image: GeoArt/Shutterstock.com

Figure 2 The effect on wave frequency as the source moves through a medium

Moving detector

Now consider the case where the wave detector is moving. If the wave detector moves towards the wave source, the wave speed relative to the detector will increase. If the wave detector moves away from the source, the wave speed relative to the detector will decrease. Regardless of the direction the detector moves, the wavelength remains constant.

To determine the effect of this movement on frequency, we rearrange the wave equation $v = f\lambda$ to the form $f = \frac{v}{\lambda}$.

When the **detector is moving towards the source**, relative wave speed increases so the **detected frequency increases**.

When the **detector is moving away from the source**, relative wave speed decreases so the **detected frequency decreases**.

It is important to remember that, in all cases, the waves do not change speed relative to the medium.

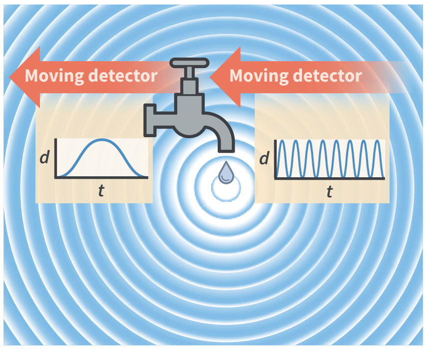


Image: GeoArt/Shutterstock.com

Figure 3 The effect on detected wave frequency as the detector moves towards and away from the source

1 Worked example

a **A motorbike rider is moving at 20 m s^{-1} towards a stationary car sounding its horn. What is the speed of the sound waves from the horn relative to the rider? Assume the speed of sound in air is 340 m s^{-1}.**

b **Would the frequency of waves observed by the rider be greater, equal or less than if the rider was stationary?**

a Relative speed is the difference in speed between the rider and the sound waves. Taking the rider's direction of motion as positive, the waves have a velocity of –340 m s^{-1} in the air:

$v_{sound\ relative\ to\ rider} = 20 - (-340) = 360\ \text{m s}^{-1}$

b The frequency would be greater than if the rider was stationary, because relative motion of a detector towards the source increases detected frequency.

The Doppler effect 4.1.6.2

OVERVIEW

The Doppler effect is the detected frequency change due to the relative motion between a wave source and detector.

THEORY DETAILS

Based on conclusions made for the different cases of relative motion, the Doppler effect can be described as:

- the **increase in wave frequency** when source and detector are **moving towards** each other, and
- the **decrease in wave frequency** when source and detector are **moving away** from each other.

The relative motion of the source and detector can be due to either one or both moving.

The Doppler effect is observed commonly as the sudden drop in frequency when a vehicle sounding a horn or siren drives past an observer. Light can behave as a wave (this will be investigated in Chapter 10) so it can also have its frequency shifted by the Doppler effect. While the explanation for the Doppler effect is different in the case of light, since light does not require a medium to propagate, the result is the same: light from stars that are moving towards the earth is blue-shifted (increase in detected frequency) and light from stars moving away is red-shifted (decrease in detected frequency).

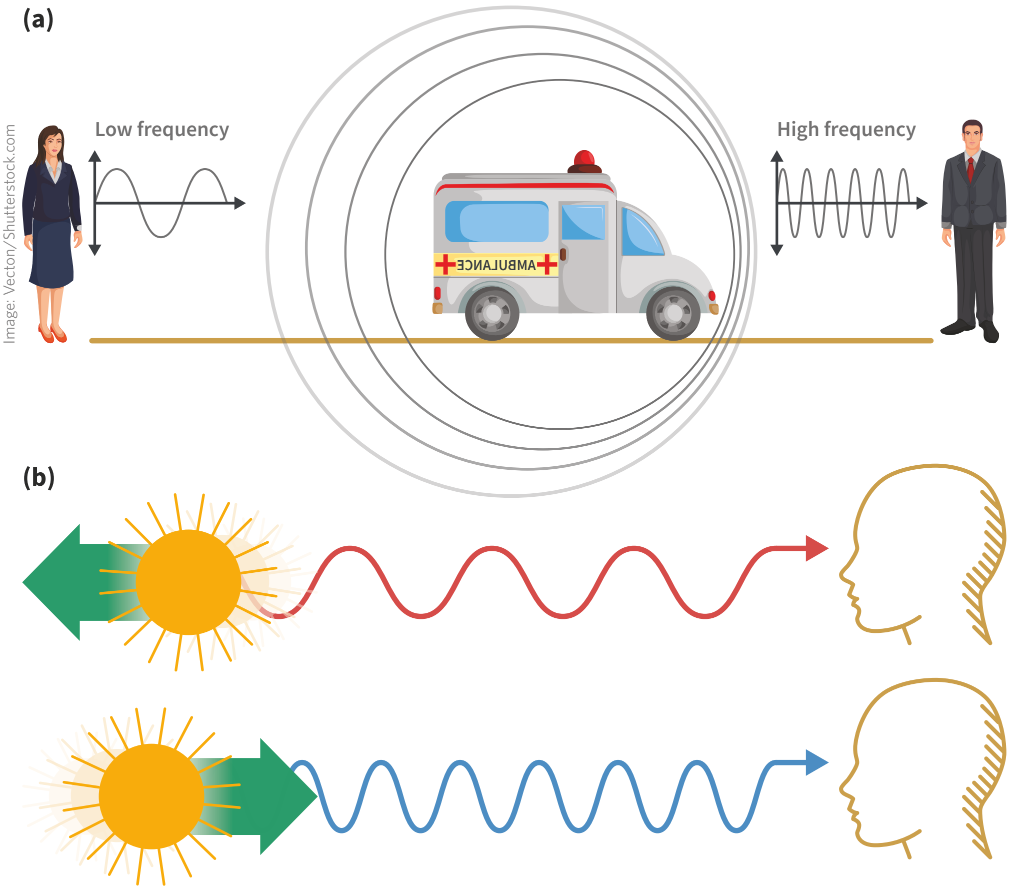


Image: Vecton/Shutterstock.com

Figure 4 Examples of the Doppler effect. **(a)** The measured frequency of an ambulance siren depends on the relative motion of the ambulance and the observer. **(b)** The measured frequency of light from a star depends on the relative motion of the star and the observer.

Theory summary

The speed of a wave is not affected by the movement of its source or a detector, however the relative motion between the wave source and detector affects the properties of the detected waves. The Doppler effect describes the general result for such motion:

- relative motion of source and detector towards each other increases frequency.
- relative motion of source and detector away from each other decreases frequency.

KEEN TO INVESTIGATE?

oPhysics 'The Doppler effect and sonic boom' simulation
https://ophysics.com/w11.html

9C Questions

THEORY REVIEW QUESTIONS

Question 1

A motorbike is travelling at speed v_m along a straight road when an oncoming car with speed v_c sounds its horn. The speed of sound in air is v_s. What is the speed of the sound waves relative to the motorbike?

A $v_s + v_m$

B $v_s - v_m$

C $v_m + v_c$

D $v_m + v_c + v_s$

Question 2

A cyclist is travelling at speed v_c and rings their bell. The speed of sound in air is v_s. What is the speed of the sound waves relative to the cyclist?

A $v_s + v_c$

B $v_s - v_c$

C v_s

D v_c

Question 3

A police car with its sirens on is initially stationary, then drives away from a pedestrian. How do the sound waves reaching the pedestrian change, as observed by the pedestrian?

A The speed of the sound waves has decreased.

B The speed of the sound waves has increased.

C The frequency of the sound waves has decreased.

D The frequency of the sound waves has increased.

Question 4

A student is walking to class and is moving away from the source of the school bell. Compared to the frequency of waves that would be observed if the student was stationary, the frequency of waves reaching the student while moving away from the bell has

A not changed.

B decreased.

C increased.

D Not enough information to conclude

Question 5

An air traffic controller observes the sound from a plane that is initially stationary, and then moves towards her. What wave property changes when the plane moves towards her, and how does it change?

A Wavelength decreases

B Wavelength increases

C Wave speed increases

D Wave period increases

Question 6

A football player is running towards an umpire blowing a whistle. What is the effect on the sound waves reaching the player, compared to if the player was stationary?

A The wavelength has increased.

B The wavelength has decreased.

C The frequency has increased.

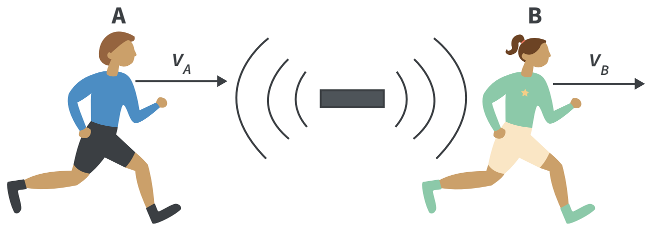
D There is no effect on the waves heard.

EXAM-STYLE QUESTIONS

This lesson

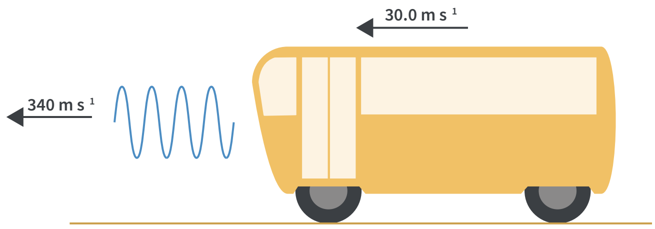
Question 7 (2 MARKS)

The diagram shows student A running towards a sound source at speed v_A and student B running away from the sound source at speed v_B. What is the speed of the sound relative to student A and student B, given the speed of sound is v_S?



Question 8 (1 MARK)

A bus is driving at 30.0 m s^{-1} along a highway, sounding its horn. What is the speed of the sound waves emitted, relative to the bus? Assume the speed of sound in air is 340 m s^{-1}.



Question 9 (2 MARKS)

Tahlia is stationary on a football oval and measures the speed of sound from an umpire's whistle as the umpire runs towards and then away from her at 8.00 m s^{-1}. What is the speed of sound measured by Tahlia in each case? The speed of sound in air is 340 m s^{-1}.

Question 10 (2 MARKS)

A student hears a police siren from a stationary police car. The car begins to move towards them. Compared to the sound waves from the stationary car, the sound heard by the student has increased frequency. Explain why, and name the physical principle involved.

Question 11 (1 MARK)

A fire engine is moving away from a pedestrian, sounding its siren. Compared to the fire engine being stationary, qualitatively describe the change in distance between wave fronts reaching the pedestrian.

Question 12 (2 MARKS)

A wave receiver is travelling away from a sound source. Describe the sound received compared to if the receiver was stationary. Explain your answer, and state the relevant physics principle involved.

Question 13 (2 MARKS)

Draw a diagram of a moving sound source to visually represent the Doppler effect. Include the sound waves in front of and behind the source.

Question 14 (5 MARKS)

Two cars are on a quiet road. Car *A* is equipped with a constant frequency wave source and car *B* with a wave detector. The detector records a measurement of wave frequency while both cars are stationary.

a Cars *A* and *B* now drive towards each other. How does the frequency of the waves recorded by car *B* compare to the waves recorded while stationary? (1 MARK)

b Car *B* now drives in front of car *A*, travelling in the same direction and at the same speed. How does the frequency of the waves recorded by car *B* compare to the waves recorded while stationary? Justify your answer. (2 MARKS)

c Car *B* now drives in front of car *A*, in the same direction but travelling faster than car *A*. How does the frequency of the waves recorded by car *B* compare to the waves recorded while stationary? Justify your answer. (2 MARKS)

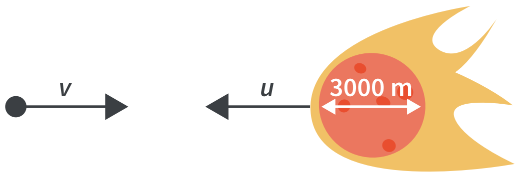
Question 15 (3 MARKS)

Mike and Tamika are discussing why wave frequency increases when a wave detector moves towards a wave source. Mike says that it is because wave speed has increased relative to the medium, but Tamika argues that Mike's reasoning is incorrect. Evaluate, using relevant theory, which student is correct and why the increase in frequency occurs.

Previous lessons

Question 16 (3 MARKS)

A comet travelling at a speed of $u = 0.05c$ relative to the Earth is hit head on by a particle moving at $v = 0.70c$ **relative to the comet**. The comet has a length of 3000 m in its own reference frame. What is the length of the comet measured in the particle's reference frame?



Adapted from 2016 VCAA Exam Section B Detailed study 1 Q7

Question 17 (2 MARKS)

Electrons are accelerated from rest in a particle accelerator by a potential difference of 40 kV. What is the final velocity of the electrons as a fraction of the speed of light? Ignore relativistic effects.

Key science skills

Question 18 (3 MARKS)

An experiment is performed to determine the effect of the speed of an approaching vehicle on the detected wave frequency. A constant 100 Hz source is used on the vehicle. What are the independent, dependent, and controlled variables?

Question 19 (2 MARKS)

Two students are investigating the Doppler effect. Tane is using a microphone connected to an oscilloscope to measure the frequency of sound waves. Bodhi is listening to the pitch of the sound. Who is using a qualitative variable and who is using a quantitative variable?

9D WAVE INTERFERENCE AND PATH DIFFERENCE

This lesson builds on the fundamental wave properties to understand the interactions between multiple waves. The result of these interactions is known as an interference pattern. It will be used as evidence of the wave behaviour of both light and matter in later chapters.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $\left(n-\frac{1}{2}\right)\lambda$ respectively

Key knowledge units

Constructive and destructive interference	4.1.5.1
How path difference affects wave interference	4.1.5.2

Formulas for this lesson

Previous lessons		New formulas
9B	* $v = f\lambda$	* Constructive: $p.d. = n\lambda$
		* Destructive: $p.d. = (n - \frac{1}{2})\lambda$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

antinode a point where constructive interference consistently occurs

coherence a property of two wave sources when they create waves of the same frequency in the same medium

interference superposition creating a larger (constructive) or smaller (destructive) resultant wave

node a point where destructive interference consistently occurs

path difference the difference in length between paths from two different wave sources to the same endpoint

superposition the addition of overlapping waves in the same medium

Constructive and destructive interference 4.1.5.1

OVERVIEW

Where two waves overlap, the result is the sum of each wave at that point. This is called interference. Interference can be constructive, if the waves have the same sign, or destructive, if the waves have opposite signs.

THEORY DETAILS

Interference occurs where waves meet one another. The result is that the waves add up at that point. This is also called superposition. After the interference occurs, the waves continue unaffected along their original path.

In Figure 1 we see constructive interference. This occurs where two waves of the same sign (both positive or both negative) interact. In this case the resultant wave is exactly double the amplitude of the individual pulses since the individual pulses have the same amplitude.

In general, the resultant wave will be larger than the individual waves.

In Figure 2 we see destructive interference. This occurs where one wave interacts with another wave of the opposite sign (one positive and one negative). In this case the two wave pulses exactly cancel each other since they have the same amplitude. In general, the resultant wave will be smaller than the individual waves.

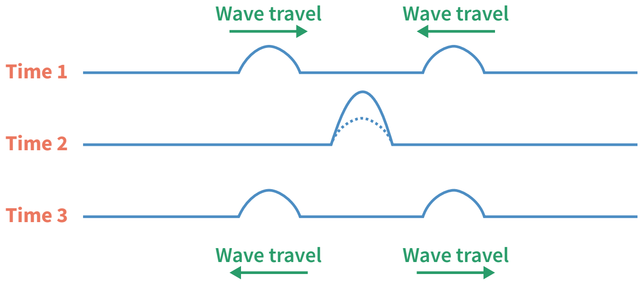


Figure 1 Constructive interference. The dashed line represents the individual wave pulses and the solid line shows the result.

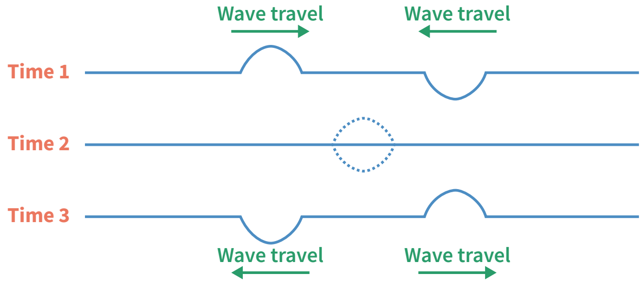


Figure 2 Destructive interference. The dashed line represents the individual wave pulses and the solid line shows the result.

In the case of sound, constructive interference means louder noise and destructive interference means quieter noise. Noise-cancelling headphones use destructive interference of sound waves to reduce ambient noise.

How path difference affects wave interference 4.1.5.2

OVERVIEW

When two coherent waves meet, the path difference at that point determines whether the waves interfere constructively or destructively.

THEORY DETAILS

Path difference

Path difference is the difference in length between paths from two different wave sources to the same endpoint:

$$p.d. = |S_1X - S_2X|$$

Path difference, as a multiple of wavelength, determines the type of interference that occurs at any given point in an interference pattern.

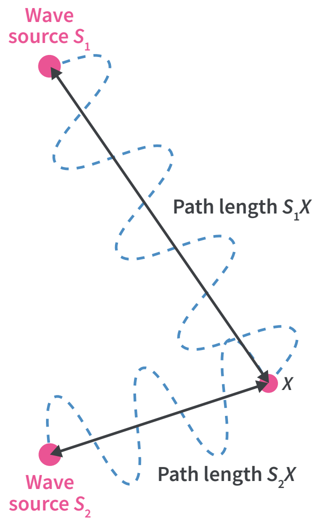


Figure 3 Path lengths from two wave sources to a point, *X*

Interference patterns

Coherent waves describe two waves with the same frequency (and wavelength, given the medium is the same for both waves). They create an interference pattern that is constant: points of constructive and destructive interference do not change. Points of consistent constructive interference (e.g. crests meet crests or troughs meet troughs) are called antinodes. Points of consistent destructive interference (e.g. crests meet troughs) are called nodes.

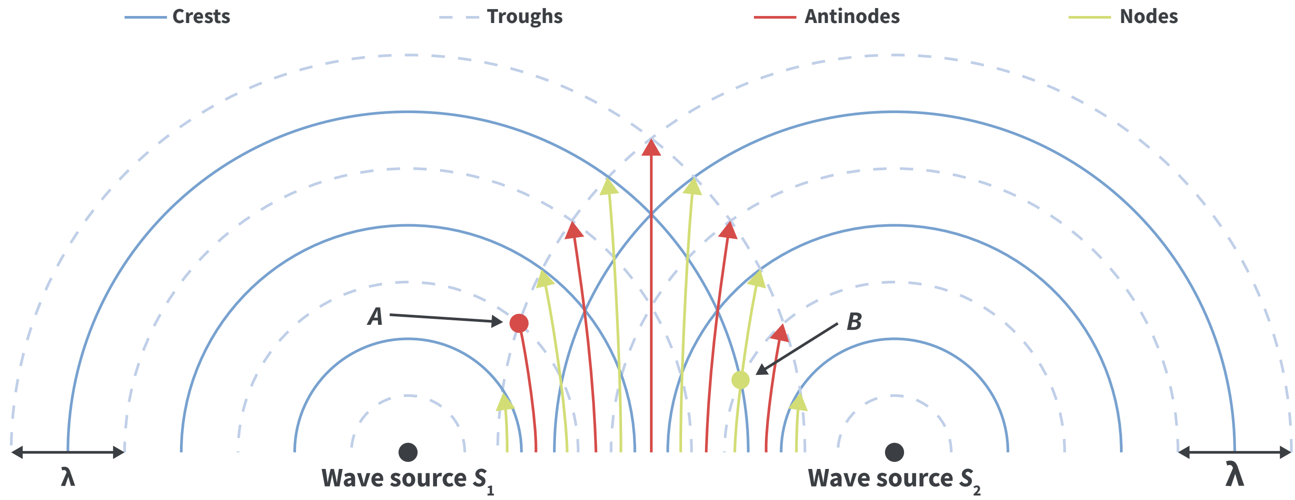


Figure 4 Interference pattern for two coherent waves. Antinodes occur where the path difference is an integer multiple of the wavelength and nodes occur where the path difference is half a wavelength less than an integer multiple of the wavelength.

Figure 4 shows coherent waves propagating from two sources and the corresponding interference pattern. It could represent ripples in water or sound waves, for example.

- Blue lines are crests (or compressions) propagating from each source.
- Dashed lines are troughs (or rarefactions) propagating from each source.
- Red lines are antinodes where consistent constructive interference occurs (blue lines meet blue lines and dashed lines meet dashed lines).
- Green lines are nodes where consistent destructive interference occurs (blue lines meet dashed lines).
- The path difference along any given red or green line is the same.
- *A* is a particular antinodal point and *B* is a particular nodal point, both of which are referred to later in the text.

Although the crests and troughs continue to propagate away from the sources (i.e. the blue and dashed lines would be in different places at another time), the locations of the antinodes and nodes do not change.

Where the path difference is an integer multiple of the wavelength, the waves will be in phase (meaning both waves are at the same stage of their cycle, e.g. both crests or both troughs) and so constructive interference occurs.

Consider point *A* in Figure 4 which is an antinode: $S_1A = 1.5\lambda$ and $S_2A = 3.5\lambda$ so $p.d. = |1.5\lambda - 3.5\lambda| = 2\lambda$. Any point along the same red line as point *A* will have $p.d. = 2\lambda$.

In general, **constructive interference** occurs where the path difference satisfies the following condition.

$$p.d. = n\lambda \quad \text{or} \quad |S_1X - S_2X| = n\lambda$$

$p.d. = |S_1X - S_2X|$ = path difference (m), λ = wavelength (m), $n = 0, 1, 2, 3, \ldots$

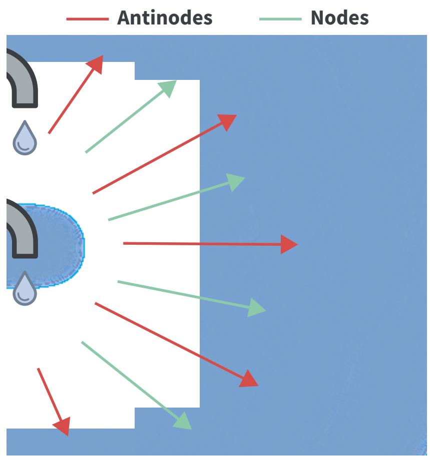


Figure 5 An interference pattern caused by coherent water ripples

Where the path difference is half a wavelength less than an integer multiple of the wavelength, the waves will be exactly out of phase (meaning the waves are at opposite stages of their cycle, e.g. crests meet troughs) and so destructive interference occurs.

Consider point *B* in Figure 4 which is a node: $S_1B = 3\lambda$ and $S_2B = 1.5\lambda$ so $p.d. = |3\lambda - 1.5\lambda| = 1.5\lambda$. Any point along the same green line as point *B* will have $p.d. = 1.5\lambda$.

In general, **destructive interference** occurs when the path difference satisfies the following condition.

$$p.d. = \left(n - \frac{1}{2}\right)\lambda \quad \text{or} \quad |S_1X - S_2X| = \left(n - \frac{1}{2}\right)\lambda$$

$p.d. = |S_1X - S_2X|$ = path difference (m), λ = wavelength (m), $n = 1, 2, 3, \ldots$

1 Worked example

Two speakers, located at point *X* and at point *Y*, are producing coherent waves with a wavelength of 1.50 m. Naomi is 6.00 m from speaker *X* and 3.00 m from speaker *Y*.

a **Determine what type of interference she is experiencing.**

b **Miriam is standing at an equal distance from both speakers. She walks in a straight line towards *Y* and stops at the third quiet region. She measures that she is 4.00 m away from speaker *X*. Calculate how far away is she from speaker *Y*.**

a We need to find the path difference where Naomi is standing.

$p.d. = |XN - YN|$

$p.d. = |6.00 - 3.00|$

$p.d. = 3.00$ m

Next we need to determine the path difference, as a multiple of the wavelength, to decide whether it fits the conditions for constructive or destructive interference.

$\frac{p.d.}{\lambda} = \frac{3.00}{1.50} = 2$

$p.d. = n\lambda$ where $n = 2$

As $\frac{p.d.}{\lambda}$ is an integer, we know that Naomi is experiencing constructive interference.

b Quiet regions imply destructive interference is occurring.

The third quiet region implies $n = 3$.

$p.d. = (n - \frac{1}{2})\lambda$

$p.d. = (3 - \frac{1}{2}) \times 1.50$

$p.d. = 3.75$ m

$|XM - YM| = 3.75$ m

$|4.00 - YM| = 3.75$ m

$YM = 0.25$ m

Miriam is 0.25 m from Y.

Theory summary

- Interference can be either constructive or destructive. Constructive interference occurs where waves of the same sign overlap and destructive interference occurs where waves of the opposite sign overlap.
- When waves from two coherent sources overlap an interference pattern is established. This pattern includes antinodes (constructive interference) and nodes (destructive interference) in fixed positions.
- The path difference to these points, as a multiple of wavelength, can show whether the point is an antinode or a node.

KEEN TO INVESTIGATE?

oPhysics 'Wave pulse interference and superposition' simulation
https://ophysics.com/w2.html

oPhysics 'Wave interference in 3D' simulation
https://ophysics.com/w12.html

PhET 'Wave interference' simulation
https://phet.colorado.edu/en/simulation/wave-interference

9D Questions

THEORY REVIEW QUESTIONS

Question 1

Two waves from coherent sources, with amplitude A, interact and perfect constructive interference occurs. What will be the amplitude of the resultant wave?

A 0

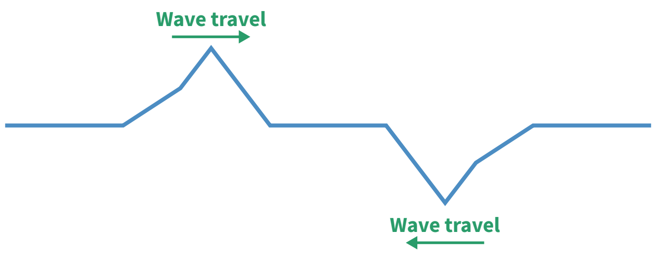
B $\frac{A}{2}$

C $2A$

D $4A$

Question 2

In the graph, what sort of interference will occur?



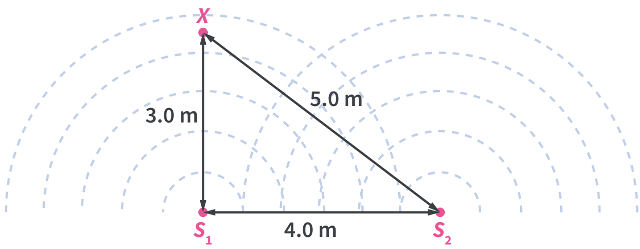
A Negative

B Destructive

C Constructive

D Superposition

Question 3



What is the path difference from the two wave sources, S_1 and S_2, at X?

A 2.0 m

B 1.0 m

C –1.0 m

D –2.0 m

Question 4

For which of the following path differences, in terms of wavelength, would a given point correspond to an antinode (consistent constructive interference)?

A 0.5λ

B 1.2λ

C 1.5λ

D 3λ

Question 5

For which of the following path differences, in terms of wavelength, would a given point correspond to a node (consistent destructive interference)?

A 0.75λ

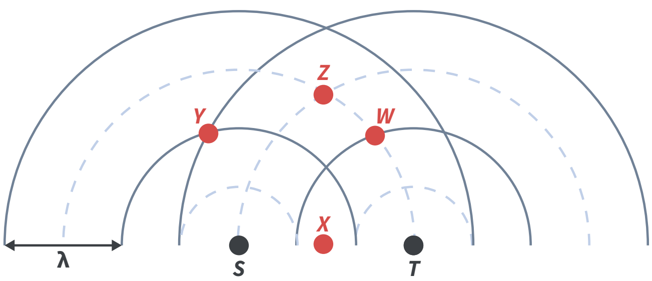
B 1.25λ

C 2.5λ

D 3λ

Question 6

Points W, X, Y, and Z all lie within the interference pattern caused by the coherent speakers at S and T.



Which option correctly identifies the antinodes and nodes?

	W	*X*	*Y*	*Z*
A	Antinode	Node	Node	Antinode
B	Node	Antinode	Antinode	Node
C	Node	Antinode	Antinode	Antinode
D	Antinode	Node	Node	Node

Question 7

The path difference from two coherent wave sources at point X is 3.0 m. For which wavelength would X be a node (consistent destructive interference)?

A 3.0 m

B 2.0 m

C 1.5 m

D 1.0 m

Question 8

Select the statement which correctly describes the interaction between waves from non-coherent sources.

A Constructive and destructive interference occurs but the positions of constructive and destructive interference change.

B Constructive and destructive interference form consistent antinodes and nodes.

C Interference occurs but it is neither constructive nor destructive.

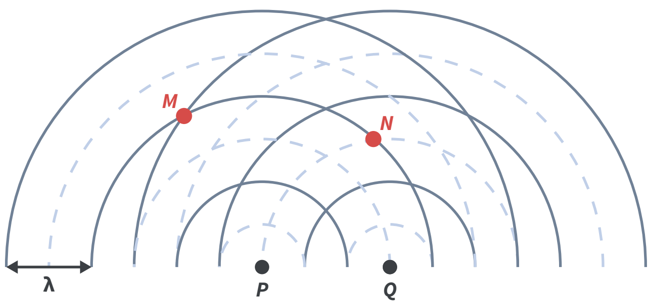
D Interference does not occur.

EXAM-STYLE QUESTIONS

This lesson

Question 9 (4 MARKS)

The diagram shows a coherent wave pattern produced by two taps, P and Q, dripping into water. The point M is an antinode at which the path difference is 4.0 cm.

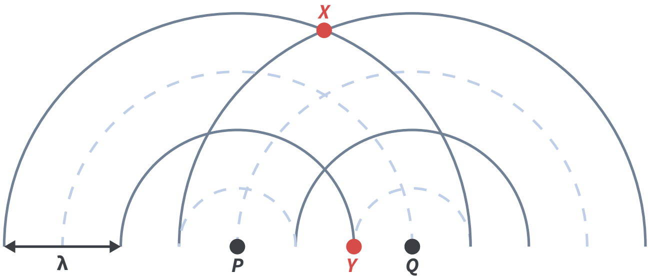


a Calculate the wavelength, λ, in centimetres. (2 MARKS)

b Using your previous answer, calculate the path difference at node N, $|QN - PN|$, in centimetres. (2 MARKS)

Question 10 (2 MARKS)

Two speakers of the same frequency, *P* and *Q*, are turned on at the same time. The diagram represents the propagating sound waves.



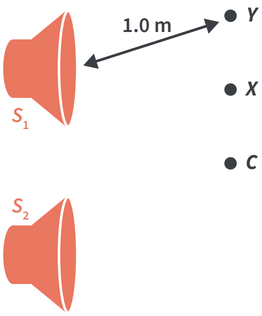
With reference to wave behaviour, explain why the sound is louder at position *X* than at position *Y*.

Question 11 (2 MARKS)

In a shallow tray of water, two point sources, *P* and *Q*, are placed producing waves of the same wavelength, $\lambda = 5.00$ cm. The point *T* is the third node from the centre and is 15.0 cm from the nearer source, *Q*. Determine the distance from *P* to *T*.

Question 12 (6 MARKS)

Two speakers are set up to play a coherent sound with a wavelength of 0.60 m. A student stands at point *C*, which is equidistant from both speakers, and then walks in a straight line recording positions where the sound is loudest. In addition to position *C*, the student records positions *X* and *Y*. Point *Y* is 1.0 m from speaker 1.



a Calculate the distance, S_2Y, from speaker 2 to point *Y*. (3 MARKS)

b The student now changes the wavelength of the sound from both speakers to 0.80 m. For this new sound, determine whether

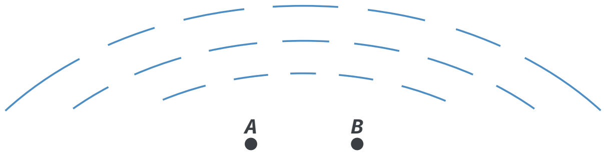
- **i** point *C* will be a point of high or low intensity sound. (1 MARK)
- **ii** point *Y* will be point of high or low intensity sound. (2 MARKS)

Question 13 (3 MARKS)

Two point sources, *A* and *B*, are creating ripples with a wavelength of 2.0 cm in a ripple tank. *X* is a point in the interference pattern 7.0 cm from *A* and 12.0 cm from *B*.

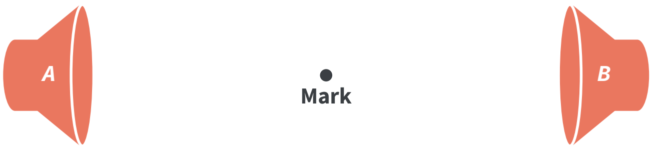
a What sort of interference occurs at point *X*? (2 MARKS)

b Copy the diagram (which is not to scale) and indicate a possible location of *X*. (1 MARK)



Question 14 (5 MARKS)

Mark stands half way between two speakers, *A* and *B*, producing a coherent sound of 680 Hz. As Mark walks towards speaker *A*, he notes alternating loud and quiet regions.



a Explain why Mark experiences the alternating loud and quiet regions. (2 MARKS)

b At the third quiet region from the centre, Mark stops. Given the speed of sound in air $v = 340$ m s^{-1}, how far did Mark travel from the centre? (3 MARKS)

Question 15 (3 MARKS)

A pool of water has two taps suspended over it. Both taps are dripping simultaneously at 4.0 Hz, creating ripples. There is an antinode at point *P* which is 2.0 cm from one of the taps and 5.0 cm from the other tap. The wavelength of the ripples is 1.5 cm.

a What is the speed of the ripples created by the dripping water? (1 MARK)

b How many antinodes from the centre is *P*? (2 MARKS)

Question 16 (3 MARKS)

Two speakers, S_1 and S_2, are set up a few metres apart on an oval. Megan walks away from the centre until she is at the third node. She is 4.50 m away from S_1 and 7.00 m away from S_2.

a Calculate the wavelength. (2 MARKS)

b The speed of sound in air is 340 m s^{-1}. What frequency are the speakers producing? (1 MARK)

Question 17 (3 MARKS)

Beyoncé sets up two speakers to simultaneously play a sound of frequency 400 Hz. She notes the position, *P*, of the first antinode from the middle. She then changes the frequency in both speakers and point *P* becomes the second node from the middle. Calculate the second frequency played.

Previous lessons

Question 18 (4 MARKS)

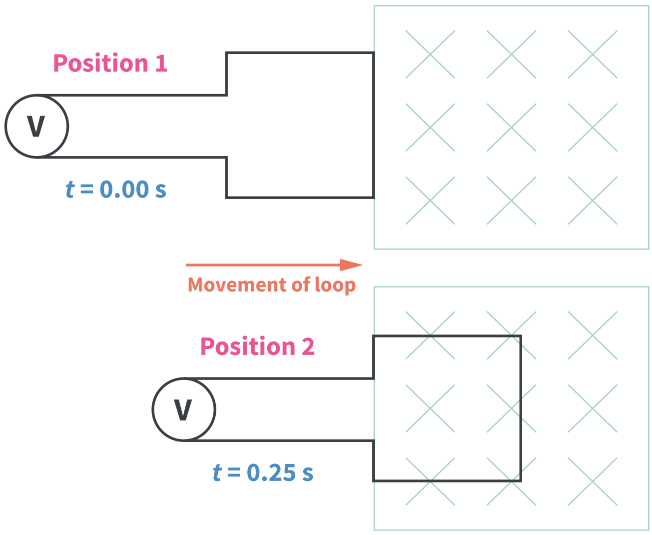
A muon passes the length of a cloud. An observer on Earth measures the cloud to be 100 m long but in the muon's reference frame the cloud is 20 m long.

a Which principle of special relativity is occurring? (1 MARK)

b How much time, measured in the muon's reference frame, does it take to pass the cloud? (3 MARKS)

Question 19 (3 MARKS)

A square loop of 15 turns and a cross-sectional area of 4.0×10^{-3} m^2 passes into a magnetic field of magnitude 2.4×10^{-2} T at a constant speed. It takes 0.25 s for the loop to travel from position 1 to 2.



Calculate the magnitude of the average emf induced in the loop as it moves from position 1 to 2.

Adapted from 2018 VCAA Exam Section B Q2

Key science skills

Question 20 (4 MARKS)

Batman is investigating sound waves and sets up two speakers to play a coherent sound with an unknown frequency. In order to measure the wavelength of the sound, he listens for the first node from the centre and measures the distance from each of the speakers to this particular node. He then uses the equation $p.d. = \left(n - \frac{1}{2}\right)\lambda$ to find the wavelength.

a Is the experimental process valid? (1 MARK)

b Identify one way to improve the reliability of the result. (1 MARK)

c Using your understanding of interference patterns, suggest one way to improve the accuracy of the result and explain how your suggestion would help. (2 MARKS)

9E RESONANCE

Resonance is a common phenomenon with spectacular effects, allowing a singer to break a glass with only their voice. It is a specific case of energy conservation, where most of the work done by a periodic external force adds energy to a system.

This lesson will explore wave resonance as a consequence of wave reflection which is important to understand standing waves in the next lesson.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration

Key knowledge units

Wave reflection	4.1.7.1
Resonance	4.1.7.2

No previous or new formulas for this lesson

Definitions for this lesson

forced oscillation the oscillation caused by the periodic application of an external driving force

natural frequency the frequency of oscillations within an object when not driven by an external periodic force

resonance the process by which the amplitude of an oscillation increases when forced oscillations match the natural frequency

resonant frequency see natural frequency

Wave reflection 4.1.7.1

OVERVIEW

Some or all of a wave's energy will be reflected back when it reaches the end of its medium.

THEORY DETAILS

When a travelling wave or wave pulse reaches the end of its medium, some or all of the wave's energy is reflected back into the medium. Consider a wave travelling along a string. When it reaches the end of the string, it will encounter either a fixed end (where the end cannot oscillate) or free end (where the end can oscillate), and be reflected back along the string. The type of end encountered affects the orientation of the reflection.

Fixed ends reflect and invert the wave.

Free ends reflect but do not invert the wave.

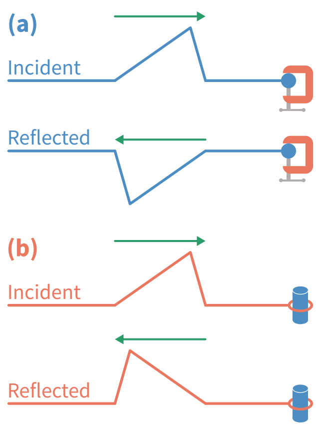


Figure 1 The incident and reflected wave pulses for **(a)** fixed and **(b)** free ends

Resonance 4.1.7.2

OVERVIEW

Forcing the oscillation of an object or string at its natural frequency will cause resonance, leading to a large increase in the amplitude of oscillations.

THEORY DETAILS

An object or system undergoes forced oscillations when acted on periodically by a force such as plucking a string, vibrating a glass with sound, or pushing a playground swing. This driving force has its own frequency at which it oscillates the object or system.

Additionally, any object or system that can vibrate has one or more natural frequencies at which vibrations within the object/system will oscillate if it is disturbed. We can see this by pushing a mass hanging on a spring or a pendulum bob. The natural frequency is determined by physical properties only (it is independent of the magnitude of the disturbance/force applied), and can also be referred to as the resonant or resonance frequency.

If the frequency of forced oscillation is equal to the natural frequency of the object/system, resonance will occur. As a result the amplitude of oscillation will significantly increase. During resonance, each forced oscillation adds energy to the oscillation of the object/system. This contrasts to a forced oscillation not at the natural frequency, where the force can act against the oscillating motion, reducing energy. An example of this principle being applied is a playground swing: to push the swing higher, you must push (force oscillation) at just the right time (the natural frequency). Resonance can lead to spectacular results. When a singer (or any sound source) produces sound waves at the natural frequency of glass, it can vibrate so violently that it shatters.

The natural frequency of a string depends on the time it takes for a wave to travel along the string, reflect, and return to its origin. If another wave is forced just as the first wave returns to the origin, the energy of each wave will sum to a larger amplitude through wave interference. Figure 2 demonstrates this process using wave pulses.

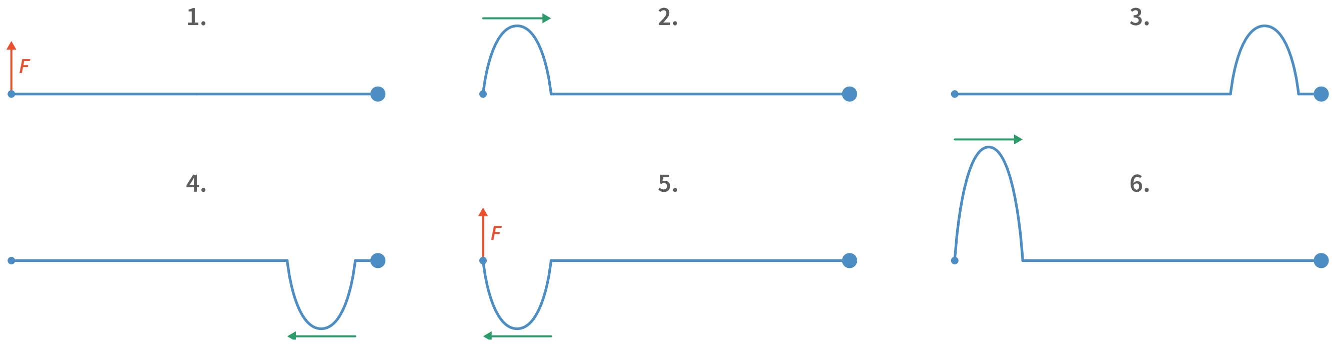


Figure 2 The process of a periodic force *F* acting at the natural frequency of a string with a fixed end, causing wave pulse amplitude to increase

Lesson 9F will examine the wave patterns that form on resonating strings.

Theory summary

- Waves reflect at the end of a string and are inverted if the end is fixed.
- An object or system will resonate if it is driven at its natural frequency.
- The superposition of reflections and travelling waves on a string can cause resonance.
- Resonance greatly increases the magnitude of oscillation in an object or system.

KEEN TO INVESTIGATE?

oPhysics 'Wave pulse reflection' simulation
https://ophysics.com/w9.html

PhET 'Wave on a string' simulation
https://phet.colorado.edu/en/simulation/wave-on-a-string

9E Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following physical characteristics can affect the natural frequency/frequencies of an object?

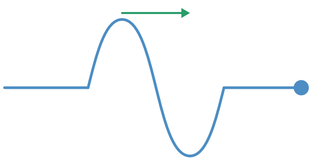
A The size of the object

B The material of the object

C The shape of the object

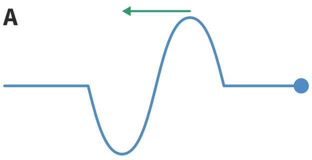
D All of the above

Question 2

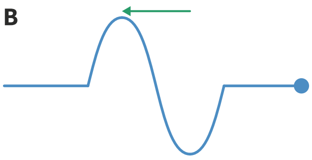


A wave pulse is reflected by the fixed end of a string. Which option shows the reflected pulse?

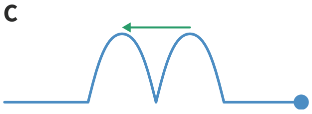
A



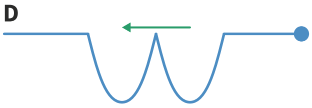
B



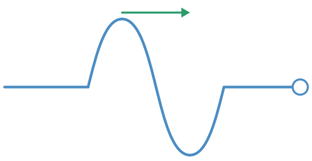
C



D

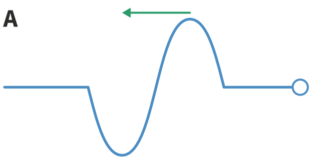


Question 3

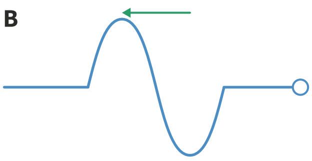


A wave pulse is reflected by the free end of a string. Which figure shows the reflected wave?

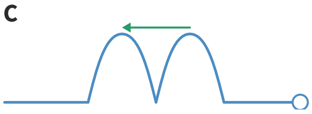
A



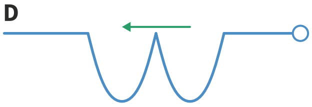
B



C



D



Question 4

Wave resonance occurs when

A the amplitude of the external driving force is large enough.

B the forcing frequency is fast enough.

C the forcing frequency is equal to the natural frequency.

D the external driving force is not periodic.

Question 5

The amplitude of oscillation observed when an object is forced at its natural frequency is

A greater than when forced at other frequencies.

B smaller than when forced at other frequencies.

C the same as when forced at other frequencies.

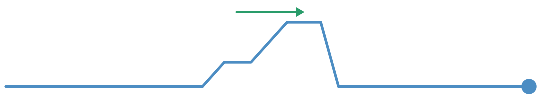
D always sufficiently large to break the object.

EXAM-STYLE QUESTIONS

This lesson

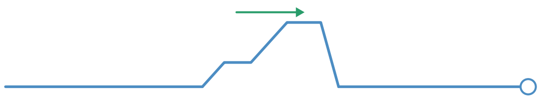
Question 6 (4 MARKS)

a A wave pulse travels down a string towards a fixed end.



Sketch the wave pulse after it has been reflected and indicate the direction of travel. (2 MARKS)

b The end of the string is changed from a fixed to a free end.



Sketch the wave pulse after it has been reflected and indicate the direction of travel. (2 MARKS)

Question 7 (1 MARK)

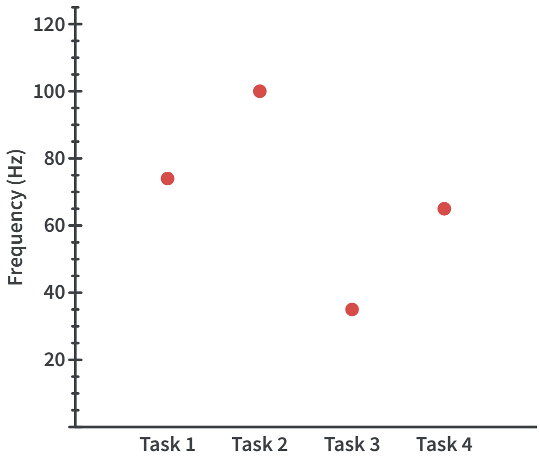
Students are trying to determine the natural frequency of an object that can vibrate by forcing oscillation at various frequencies. How will the students know when they are driving oscillation at the natural frequency?

Question 8 (2 MARKS)

Explain why, at a certain frequency, objects resonate. Use your explanation to describe how a human voice is able to shatter a glass.

Question 9 (2 MARKS)

The graph shows the frequency of oscillation associated with a machine performing different tasks. The machine has a resonant frequency of 75 Hz. Which task will cause the machine to vibrate the most, and why?



Question 10 (3 MARKS)

Two fathers are arguing over the most effective way to push their children higher on a swing. George says that pushing at the highest frequency possible is the most efficient way of achieving a high swing. He reasons that each push does work on the system, so more frequent pushes will result in a higher swing. Francis argues that there is a more efficient way of achieving a high swing.

Who is correct? Explain the reasoning behind your decision.

Previous lessons

Question 11 (3 MARKS)

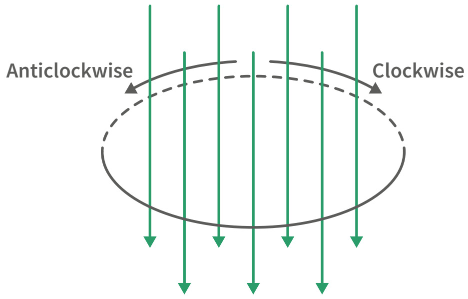
An observer notices that a clock on a passing 1.2×10^5 kg train is running at half the speed of their watch. What is the kinetic energy of the train in the observer's reference frame if the train is not accelerating?

Question 12 (3 MARKS)

A charged particle with $\gamma = 4.5$ and mass m collides with a second, larger particle which is initially stationary. The kinetic energy of the first particle after the collision is mc^2. What is the kinetic energy of the second particle if kinetic energy is conserved in the collision? Give your answer as a multiple of mc^2.

Question 13 (2 MARKS)

The magnetic flux through a circular loop of resistance 0.5 Ω is reduced from a positive value pointing down the page to zero. In what direction (clockwise or anticlockwise) does the induced current pass around the loop? Why does the current flow this way?



Key science skills

Question 14 (5 MARKS)

Scientists conduct an experiment to determine the natural frequency of a new radar dish. They force oscillation at a range of frequencies and record the amplitude of oscillation on the dish.

Forcing frequency (Hz)	Oscillation amplitude (m)
20	0.30
40	0.40
45	0.85
50	0.40
70	0.30

The measurement uncertainty of the oscillation amplitude is ± 5 cm.

a Sketch a graph of the scientists' data, fitting an appropriate curve to the graph. Be sure to include uncertainty bars. (4 MARKS)

b What is the approximate natural frequency of the radar dish? (1 MARK)

9F STANDING WAVES

Standing waves are particular kinds of waves that appear to be oscillating on the spot instead of travelling. Standing waves can form on a string when travelling waves interfere with their reflections. This lesson will build on the concept of resonance to examine what a standing wave is and the properties of standing waves in strings that have one or both ends fixed.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- analyse the formation of standing waves in strings fixed at one or both ends

Key knowledge units

Standing waves with two fixed ends	4.1.8.1
Standing waves with one fixed end	4.1.8.2

Formulas for this lesson

Previous lessons		New formulas
9B	* $v = f\lambda$	$\lambda = \frac{2L}{n}$
		$f = \frac{nv}{2L}$
		$\lambda = \frac{4L}{n}$ for odd values of n
		$f = \frac{nv}{4L}$ for odd values of n

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

fundamental frequency the lowest frequency of a standing wave in a given medium

harmonic a standing wave with a frequency equal to an integer multiple of the fundamental frequency

standing wave a wave for which the positions of maximum amplitude (antinodes) and zero amplitude (nodes) are constant; a superposition of two waves travelling in opposite directions with the same frequency and amplitude

stationary wave see standing wave

travelling wave a wave for which the crests and troughs (or compressions and rarefactions) travel in the direction of wave propagation

Standing waves with two fixed ends 4.1.8.1

OVERVIEW

Standing waves with two fixed ends are formed by the superposition of two identical waves travelling in opposite directions to produce an interference pattern. They always have nodes at both fixed ends.

THEORY DETAILS

Formation

When two waves with the same amplitude and frequency travel in opposite directions, an interference pattern forms from their superposition.

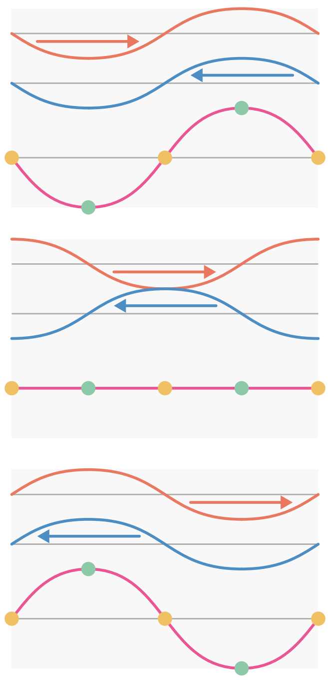


Figure 1 Three images show three different points in time for a standing wave (pink) which is formed by the superposition of a wave travelling right (orange) and its inverted reflection travelling left (blue) from a fixed end. Antinodes (green dots) and nodes (yellow dots) are shown.

This interference pattern is called a standing wave, or stationary wave, because it has fixed nodes and antinodes. The resulting wave has an amplitude that changes with time but the positions of maximum amplitude (antinodes) and zero amplitude (nodes) are constant. The wave does not appear to travel.

On a string, a standing wave can form due to the superposition of a travelling wave and its reflection (which has the same frequency and amplitude). As explained in lesson 9E, when a wave on a string hits a fixed end the reflected wave will be inverted. The fixed ends must be nodes, always undergoing destructive interference, because they are physically restrained. A standing wave will form if the frequency of the travelling wave is a resonant frequency of the string. For other frequencies a standing wave will not form because the returning waves will not be in phase with the forced oscillations.

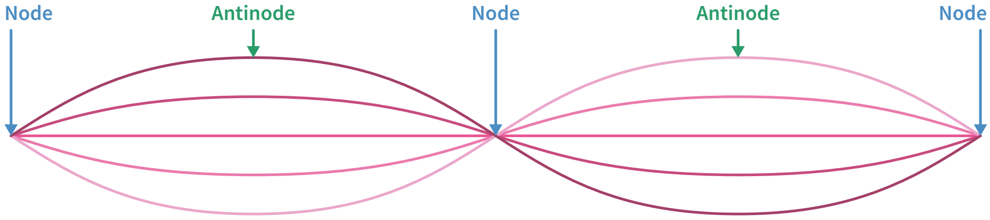


Figure 2 Motion of a standing wave with two fixed ends. The darkest line shows the starting position and the lightest line shows the position after half of a period. This is a second harmonic standing wave.

Harmonics

Standing waves on strings are constrained by the existence of nodes and/or antinodes at the string ends. This means only certain wavelengths and frequencies of standing waves can form on a given length of string which correspond to the resonant frequencies of the string. The various frequencies of standing waves are called harmonics and are designated by a harmonic number, n, which is always an integer.

On a string with **two fixed ends**, there must be a **node at both ends** of the standing wave. The first harmonic ($n = 1$) is the fundamental (lowest) frequency. This corresponds to the longest wavelength which meets the constraints: there is a node at each end and one antinode in the middle of the string so the wavelength is double the length of the string. Higher harmonics have shorter wavelengths and higher frequencies than the fundamental frequency.

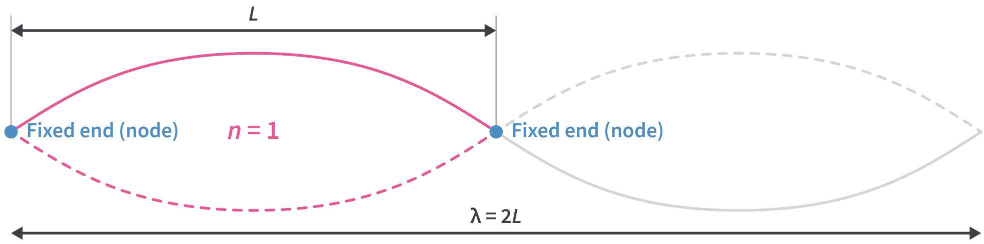


Figure 3 For a standing wave with two fixed ends at the fundamental frequency, the length of the string is half of the wavelength of the wave. The grey lines represent the imaginary continuation of the wave.

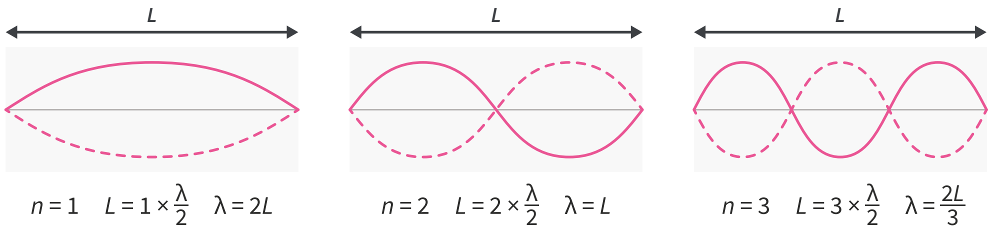


Figure 4 The first three harmonics for standing waves on strings with two fixed ends

USEFUL TIP

We can think of the harmonic number of a standing wave with two fixed ends as the number of half-wavelength "packets" that fit into the length of the string $\left(L = n\frac{\lambda}{2}\right)$.

For strings with two fixed ends, the wavelength and frequency of standing waves can be calculated by the following formulas.

$$\lambda = \frac{2L}{n}$$

λ = wavelength (m), n = harmonic number (1,2,3,…), L = string length (m)

$$f = \frac{v}{\lambda} = \frac{nv}{2L}$$

f = frequency (Hz), n = harmonic number (1,2,3,...), v = wave speed (m s^{-1}), L = string length (m)

1 **Worked example**

A string with a length of 3.00 m is tied firmly between two trees. A series of waves are sent along the string (travelling at 300 m s^{-1}) such that a fourth harmonic standing wave is formed. What is the wavelength and frequency of this wave?

As both ends of the string are tied tightly to the two trees, the two ends of the string are fixed. A fourth harmonic means $n = 4$.

$\lambda = \frac{2L}{n}$

$\lambda = \frac{2 \times 3.00}{4}$

$\lambda = 1.50$ m

$f = \frac{nv}{2L}$

$f = \frac{4 \times 300}{2 \times 3.00}$

$f = 200$ Hz

Given that we had already calculated λ, we could have found the frequency using the wave equation: $f = \frac{v}{\lambda} = \frac{300}{1.50} = 200$ Hz

The wavelength of the wave is 1.50 m and the frequency of the wave is 200 Hz.

Standing waves with one fixed end 4.1.8.2

OVERVIEW

Standing waves with one fixed end and one free end are again formed by the superposition of two identical waves travelling in opposite directions. They always have a node at the fixed end and an antinode at the free end.

THEORY DETAILS

Formation

The formation of standing waves on a string with one fixed end and one free end is very similar to that for a string with two fixed ends. The only difference is that the free end must be an antinode. This is because waves reflected at the free end are not inverted and so constructive interference occurs at this end.

Harmonics

On a string with **one fixed end**, standing waves are constrained by the fact that there must be a **node at the fixed end** and an **antinode at the free end**. To meet this constraint, only odd harmonics can form, so n must be an odd integer.

At the fundamental frequency, or first harmonic ($n = 1$), the wavelength is the longest wavelength which meets the constraints: there is a node at one end and an antinode at the other end so the wavelength is four times the length of the string.

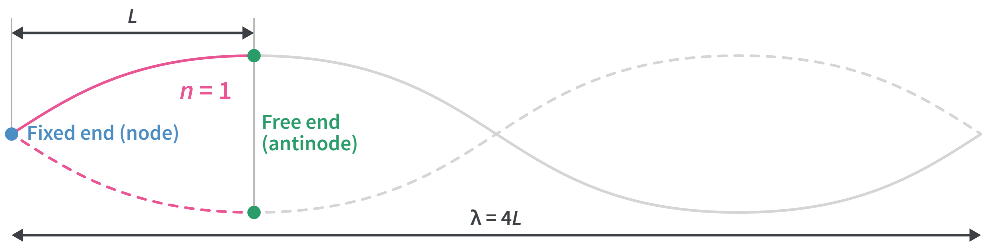
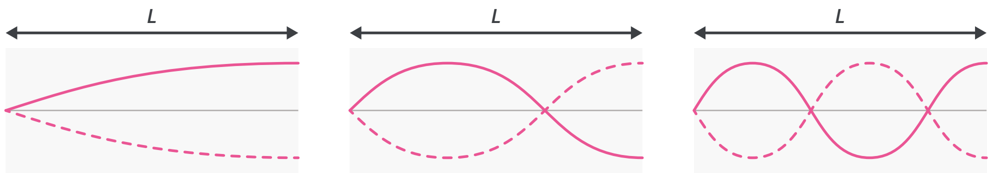


Figure 5 For a standing wave with one fixed end at the fundamental frequency, the length of the string is one quarter of the wavelength of the wave. The grey lines represent the imaginary continuation of the wave.

USEFUL TIP

We can think of the harmonic number of a standing wave with one free end as the number of quarter-wavelength "packets" that fit into the length of the string $\left(L = n\frac{\lambda}{4}\right)$. As there must be an antinode at the free end of the string, there must be an odd number of quarter-wavelength "packets", so only odd harmonics can form.



$n = 1 \quad L = 1 \times \frac{\lambda}{4} \quad \lambda = 4L$ $\qquad n = 3 \quad L = 3 \times \frac{\lambda}{4} \quad \lambda = \frac{4L}{3}$ $\qquad n = 5 \quad L = 5 \times \frac{\lambda}{4} \quad \lambda = \frac{4L}{5}$

Figure 6 The first, third, and fifth harmonics for standing waves on strings with one fixed end

For strings with one fixed end, the wavelength and frequency of standing waves can be calculated by the following formulas.

> $\lambda = \frac{4L}{n}$ **for odd values of n**
>
> **λ = wavelength (m), n = harmonic number (1,3,5,…), L = string length (m)**

> $f = \frac{nv}{4L}$ **for odd values of n**
>
> **f = frequency (Hz), n = harmonic number (1,3,5,…), v = wave speed (m s^{-1}), L = string length (m)**

2 Worked example

A string with a length of 6.00 m is tied firmly around one tree and loosely around a metal pole so the string is free to move up and down at this end. A series of waves are sent along the string (travelling at 240 m s^{-1}) such that a third harmonic standing wave is formed. What is the frequency and wavelength of this wave?

The string has one fixed end and one free end. A third harmonic means $n = 3$.

$\lambda = \frac{4L}{n}$

$\lambda = \frac{4 \times 6.00}{3}$

$\lambda = 8.00$ m

$f = \frac{nv}{4L}$

$f = \frac{3 \times 240}{4 \times 6.00}$

$f = 30.0$ Hz

Given that we had already calculated λ, we could have found the frequency using the wave equation: $f = \frac{v}{\lambda} = \frac{240}{8.00} = 30.0$ Hz.

The wavelength of the wave is 8.00 m and the frequency of the wave is 30.0 Hz.

Theory summary

The key points in the formation of a standing wave on a string are:

- Waves reflect at both ends of the string.
- Reflections travel in opposite directions with the same amplitude and frequency.
- Wave superposition between the travelling wave and its reflection produces an interference pattern with antinodes and nodes.
- Fixed ends are nodes and free ends are antinodes.

Standing waves on a string with two fixed ends form so that the length of the string is an integer multiple of half of the wavelength. Standing waves on a string with one fixed end and one free end form so that the length of the string is an odd multiple of one quarter of the wavelength.

From these relationships, the wavelength can be derived in terms of the string length. The frequency can then be determined from the wave equation $\left(f = \frac{v}{\lambda}\right)$.

KEEN TO INVESTIGATE?

oPhysics 'Superposition of transverse waves' simulation
https://ophysics.com/w3.html

oPhysics 'Standing waves' simulation
https://ophysics.com/w7.html

oPhysics 'Standing waves on strings' simulation
https://ophysics.com/w8.html

9F Questions

THEORY REVIEW QUESTIONS

Question 1

The best description of a standing wave in a string is

A the interference of two transverse waves that travel in the same direction.

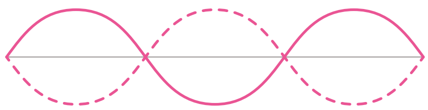
B the interference of two transverse waves that travel in the opposite direction.

C the interference of two longitudinal waves that travel in the same direction with the same frequency.

D the interference of two transverse waves that travel in the opposite direction with the same frequency and amplitude.

Question 2

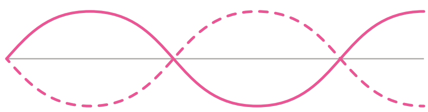
The number harmonic (*n* value) of the standing wave pictured below is



A 1.5 **B** 2 **C** 3 **D** 6

Question 3

The number harmonic (*n* value) of the standing wave pictured below is



A 1.25 **B** 2 **C** 2.5 **D** 5

Question 4

What is the fundamental frequency of a string with both ends fixed that has a length of 2.0 m and a wave speed of 100 m s^{-1}?

A 25 Hz

B 50 Hz

C 100 Hz

D 200 Hz

Question 5

What is the wavelength of the first harmonic standing wave on a string with both ends fixed that has a length of 4.0 cm and a wave speed of 400 m s^{-1}?

A 4.0 cm

B 8.0 cm

C 12 cm

D 16 cm

Question 6

What is the fundamental frequency of a wave on a string with one fixed end that has a length of 2.00 m and a wave speed of 200 m s^{-1}?

A 25.0 Hz

B 50.0 Hz

C 100 Hz

D 200 Hz

Question 7

What is the wavelength of the first harmonic standing wave on a string with one fixed end that has a length of 4.0 cm and a wave speed of 400 m s^{-1}?

A 0.04 m

B 0.08 m

C 0.12 m

D 0.16 m

EXAM-STYLE QUESTIONS

This lesson

Question 8 (4 MARKS)

A 5.0 m tightrope is tied to a tree at both ends. Waves travel at 200 m s^{-1} along the rope.

a Calculate the wavelength of the lowest frequency resonance of the rope. (1 MARK)

b Calculate the fundamental frequency of the rope. (1 MARK)

c Calculate the wavelength and frequency of the second harmonic standing wave on the rope. (2 MARKS)

Question 9 (4 MARKS)

The waves on a cello string have a speed of 330 m s^{-1}. The length of the string is 69.0 cm and both ends of the string are considered fixed.

a Calculate the wavelength of the third harmonic of the string. (1 MARK)

b Calculate the frequency of the third harmonic of the string. (1 MARK)

c The cellist then begins playing a note of a higher frequency by producing a fourth harmonic wave. Calculate the new wavelength and frequency of the standing wave in the string. (2 MARKS)

Question 10 (4 MARKS)

Consider a 0.90 m long string with one fixed end and one free end that has a wave speed of 360 m s^{-1}.

a Calculate the wavelength of the lowest frequency resonance of the string. (1 MARK)

b Calculate the fundamental frequency of the string. (1 MARK)

c Calculate the wavelength and frequency of the second lowest frequency resonance of the string. (2 MARK)

Question 11 (4 MARKS)

The 'A' string on Zoe's violin has a length of 32.5 cm and a fundamental frequency of 440 Hz. It is fixed at both ends. Zoe presses her finger halfway down the 'A' string and plays a note.

a Calculate the wavelength of the lowest frequency resonance that now forms on the string. (2 MARKS)

b Calculate the frequency of the resulting note Zoe plays. Justify your answer. (2 MARKS)

Question 12 (2 MARKS)

Alex is going to set up a standing wave at the fundamental frequency on a string with one fixed end and one free end. Alex wants the wavelength of the wave to be 3.0 m. How long should he cut the piece of string?

Question 13 (4 MARKS)

a Draw a diagram of the 1st and 3rd harmonics of a string with both ends fixed. (2 MARKS)

b Draw a diagram of the 1st and 3rd harmonics of a string with one end fixed. (2 MARKS)

Question 14 (3 MARKS)

Explain how a standing wave is formed on a string. Include a diagram in your answer.

Question 15 (2 MARKS)

Distinguish between standing waves and travelling waves with reference to locations of maximum amplitude.

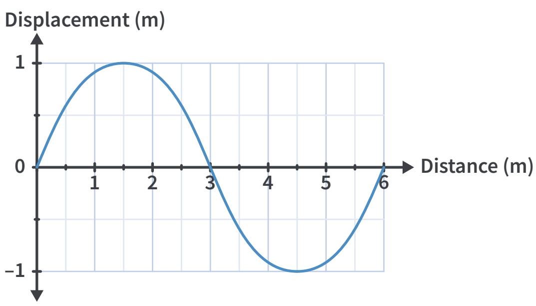
Question 16 (5 MARKS)

A fifth harmonic standing wave is formed in a string with a length of 10.0 cm. The first antinode measured from a fixed end is located 2.0 cm along the length of the rope.

a Does the string have one fixed end or two fixed ends? Justify your response. Use diagrams to support your answer. (3 MARKS)

b The speed of the wave in the string is 300 m s^{-1}. Calculate the frequency of the wave. (2 MARKS)

Question 17 (7 MARKS)



The graph shows the displacement-distance relationship for a second harmonic standing wave on a string. The period of the standing wave shown is 4.0 seconds.

a Redraw the displacement-distance graph for a time 1.0 second after that shown. (2 MARKS)

b Redraw the displacement-distance graph for a time 2.0 seconds after that shown. (2 MARKS)

c Calculate the frequency of the fifth harmonic standing wave that would form on this string. (3 MARKS)

Question 18 (2 MARKS)

Determine what length of string is needed to make a standing wave with exactly two nodes and two antinodes with a frequency of 10 Hz and a wave speed of 20 m s^{-1}.

Previous lessons

Question 19 (6 MARKS)

Two students set up a small model generator with the generator output fitted with slip rings and connected to an oscilloscope.

a Explain why the oscilloscope shows an AC signal instead of a DC signal. (2 MARKS)

b Calculate the frequency of the AC signal given that the coil of the generator makes one quarter turn every 30 ms. (2 MARK)

c Describe the effect(s) on the oscilloscope output of changing the rotation speed of the coil to be one quarter turn every 10 ms. (2 MARKS)

Adapted from 2014 VCAA Exam Section A Q18

Question 20 (2 MARKS)

Clare, an astronaut who is stationary in an inertial reference frame inside a spaceship, sees another spaceship piloted by fellow astronaut, Belle, move past her at constant velocity. Clare measures the clocks on Belle's spaceship to run 5 times slower than her clocks. Belle's spaceship has a mass of 15 000 kg.

Calculate the kinetic energy of Belle's spaceship in Clare's frame of reference.

Key science skills

Question 21 (2 MARKS)

James is measuring how the frequency of sound changes when pressing his finger down at different positions on a guitar string. James' physics teacher recommends that he:

- takes multiple readings of the frequency for each finger position, and
- has a friend repeat the experiment later.

Explain how each recommendation will improve James' experiment.

9G DIFFRACTION

Have you ever wondered how we hear sound from another room or how waves from out at sea can bend around headlands on their way to the shore? Diffraction is a behaviour of waves which helps explain these phenomena. This lesson will explore the way that wavelength and gap width or obstacle size affect diffraction.

9A Wave fundamentals	9B Wave speed	9C The Doppler effect	9D Wave interference and path difference	9E Resonance	9F Standing waves	9G Diffraction

Study design key knowledge dot point

- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio

Key knowledge units

Describing diffraction	4.1.9.1
Analysing diffraction	4.1.9.2

Formulas for this lesson

Previous lessons		New formulas
9B	* $v = f\lambda$	diffraction $\propto \frac{\lambda}{w}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

aperture a hole, gap, or slit through which a wave travels

diffraction the spread of a wave around an obstacle or through an aperture

Describing diffraction 4.1.9.1

OVERVIEW

Diffraction describes how waves spread around obstacles and through gaps.

THEORY DETAILS

Diffraction occurs every time a wave interacts with the edge of an obstacle. Unlike particles, when a wave interacts with an obstacle the wave spreads around it rather than being blocked. This is explained by Huygen's principle (which is beyond the scope of this course).

A gap, which is commonly referred to as an aperture in the context of waves, can be seen as the space between the edges of two obstacles so diffraction occurs through a gap in a similar fashion. As a wave moves through the gap it spreads around both sides. In this way, sound originating in one room can pass through a doorway and spread into the next room.

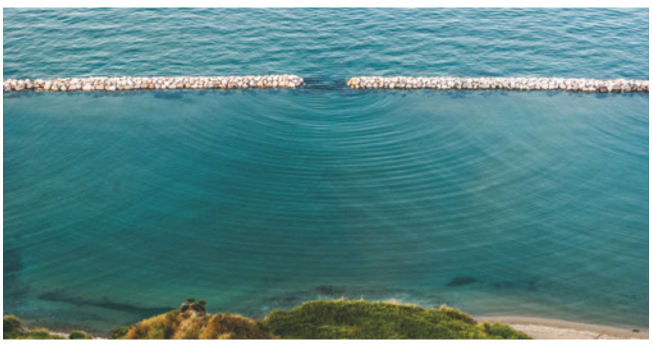


Figure 1 Water waves from the ocean diffracting through a rock wall

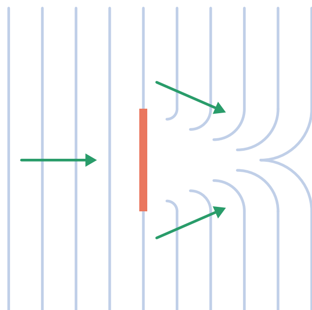


Figure 2 Waves diffract around an obstacle.

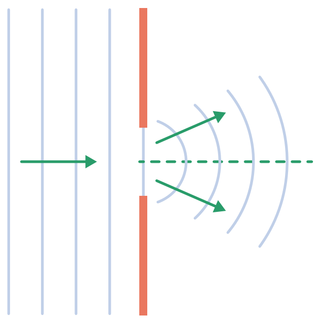


Figure 3 Waves diffract through a gap. The dashed line divides the pattern in half showing the similarity with diffraction around an obstacle.

Analysing diffraction 4.1.9.2

OVERVIEW

The amount that a wave diffracts when it meets an obstacle or gap depends on the wavelength and the size of the obstacle or gap.

THEORY DETAILS

The extent (amount) of diffraction is proportional to the ratio of wavelength to obstacle/gap width.

$$\text{diffraction} \propto \frac{\lambda}{w}$$

λ = wavelength (m), w = obstacle/gap width (m)

This means that waves with longer wavelengths (lower frequencies) will diffract more than waves with shorter wavelengths (higher frequencies). We experience this when we hear the heavy bass in a song from another room more clearly than the treble (higher frequency notes). It also means smaller obstacles/gaps will cause greater diffraction than larger ones.

For the purposes of VCE study, diffraction is a qualitative behaviour. The extent of diffraction is typically considered significant when the wavelength is of the same magnitude or larger than the width; that is, when $\frac{\lambda}{w} \geq 1$.

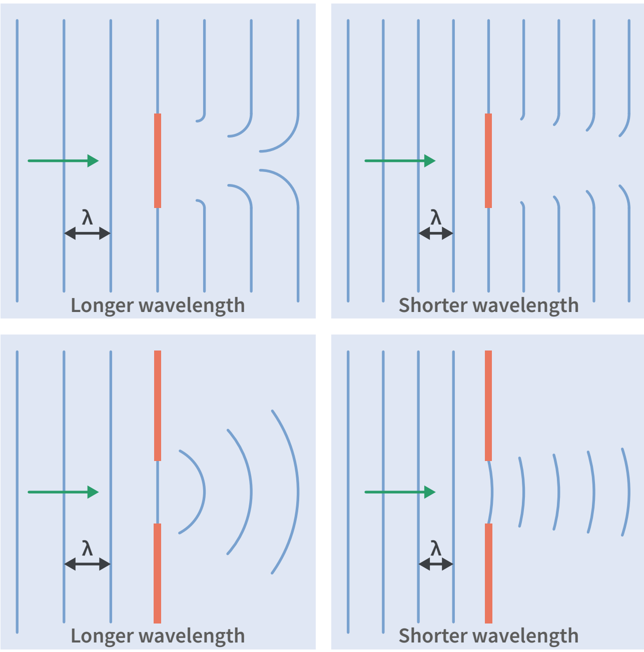


Figure 4 For a given obstacle/gap width, a longer wavelength diffracts more than a shorter wavelength.

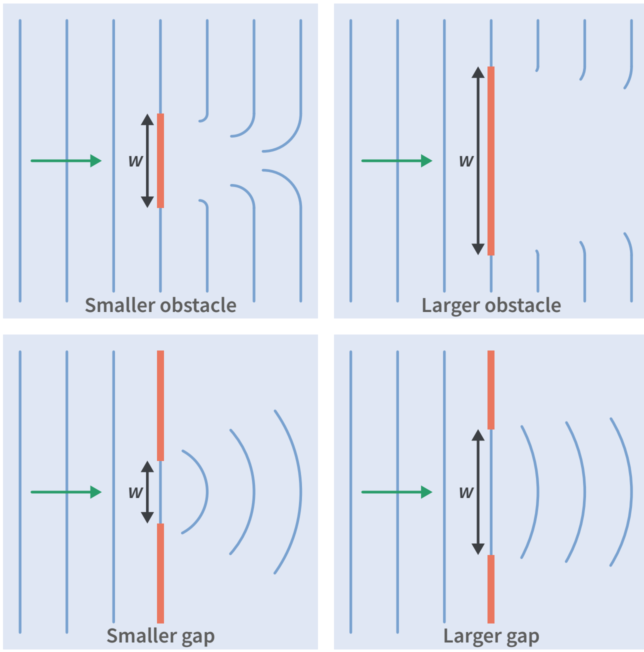


Figure 5 For a given wavelength, a smaller obstacle/gap width will cause more diffraction than a larger width.

Theory summary

- Diffraction is the way that waves spread around obstacles and through gaps.
- The greater the value of the ratio $\frac{\lambda}{w}$ the more significant the diffraction.

KEEN TO INVESTIGATE?

PhET 'Wave interference' simulation

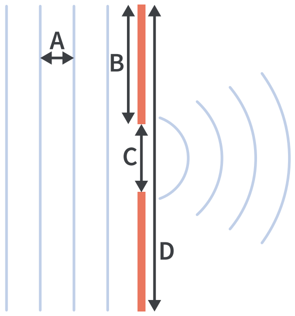
https://phet.colorado.edu/en/simulation/wave-interference

9G Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following distances (A, B, C, or D) is the gap width in this scenario?



Question 2

Diffraction is best defined as

A the change in the speed of a wave as it passes an obstacle or gap.

B the spreading behaviour of waves around an obstacle or through a gap.

C the pattern formed by two waves when they interact.

D the ratio of wavelength to width.

Question 3

For a given wavelength, which of the following gap widths will cause the greatest diffraction?

A 0.10 m **B** 0.20 m **C** 0.30 m **D** 0.40 m

Question 4

For a given gap width, which of the following wavelengths will diffract most?

A 0.10 m **B** 0.20 m **C** 0.30 m **D** 0.40 m

Question 5

For a given gap width and wave medium, which of the following frequencies will diffract the most?

A 10 Hz **B** 20 Hz **C** 30 Hz **D** 40 Hz

Question 6

For ripples of water passing through a gap, which of the following combinations of wavelength and gap width will lead to the most significant diffraction?

A $\lambda = 1.0$ m, $w = 1.0$ m

B $\lambda = 2.0$ m, $w = 1.0$ m

C $\lambda = 1.0$ m, $w = 2.0$ m

D $\lambda = 2.0$ m, $w = 2.0$ m

EXAM-STYLE QUESTIONS

This lesson

Question 7 (1 MARK)

In which of these situations is diffraction most likely to be responsible for the observation?

A A student notices regions of high intensity and low intensity sound while walking around a field with two coherent speakers.

B Wave crests travelling along a rope reach a wall and return as troughs.

C The pitch of an ambulance siren is observed to change as it drives past.

D The lower pitch sound of a siren on a stationary ambulance around a street corner is heard more clearly than the higher pitch sound.

Question 8 (2 MARKS)

Two speakers are producing sound at the same intensity in a room. Speaker *A* is producing sound with a 1.0 m wavelength and speaker *B* is producing sound with a 3.0 m wavelength. Which speaker can be heard with greater intensity around the corner from a 2.0 m door? Justify your answer with supporting calculations.

Question 9 (4 MARKS)

The diagram shows waves in a ripple tank passing through a slit in a barrier.

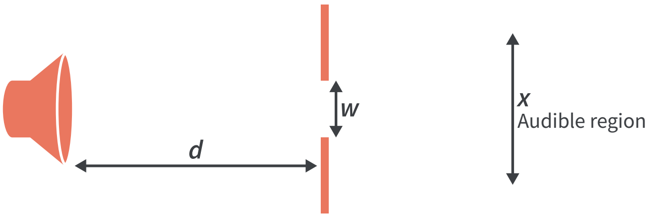
The frequency of the incident waves is then increased.

a Copy the diagram with the original frequency (for comparison), and draw a new diagram showing the pattern for the higher frequency. (2 MARKS)

b Explain the change in the diffraction pattern. (2 MARKS)

Question 10 (3 MARKS)

The diagram shows a speaker playing a single frequency, f, which is placed a distance, d, from a soundproof barrier which has a gap of width, w. Three students measure the width of the audible region on the other side of the barrier to be x. They want the audible region to be approximately $2x$. To achieve this, Hannah suggests using a frequency of $\frac{f}{2}$. Ash suggests moving the speaker closer to a distance, $\frac{d}{2}$. Shahan suggests using a gap width of $2w$.



Evaluate these three suggestions.

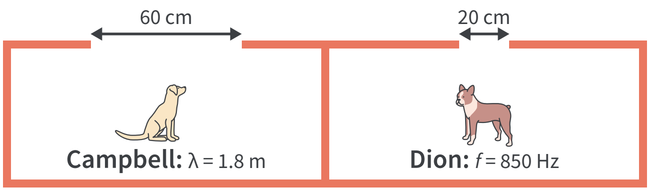
Question 11 (2 MARKS)

A trombonist is practising slides along her trombone's frequency range. She wants to show this off by leaving the door open. A pianist is jealously listening outside the door and notices that the sound gets quieter during each slide. Is the trombonist sliding up or down the frequency range? Justify your answer.

Question 12 (3 MARKS)

Campbell is a large dog in a kennel with a 60 cm opening. He barks with a wavelength of 1.8 m. Dion is a small dog in a kennel with a 20 cm opening and he barks with a frequency of 850 Hz. Both dogs are barking with same sound intensity.

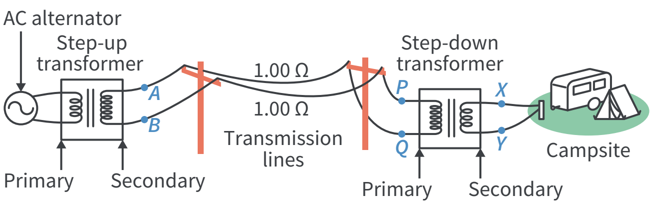
Which of the dogs' barks will diffract more? Use calculations to justify your answer. Assume the speed of sound in air is 340 m s^{-1}.



Previous lessons

Question 13 (7 MARKS)

An AC alternator is used to power a distant campsite. The alternator produces 140 V_{RMS} and a current of 40.0 A_{RMS}. In order to reduce the power loss to the campsite, a 1:4 step-up transformer is used between the alternator and the transmission lines – which have a resistance of 1.00 Ω in each line – and a 4:1 step-down transformer is used between the transmission lines and the campsite.



Adapted from 2009 VCAA Exam 2 Section A Q12–15

a Calculate the peak voltage produced by the alternator. (1 MARK)

b There are 2000 turns in the primary winding of the step-down transformer. How many turns are in the secondary winding? (1 MARK)

c What is the power loss in the transmission lines? (2 MARKS)

d What is the voltage reaching the campsite, V_{XY}? (3 MARKS)

Question 14 (2 MARKS)

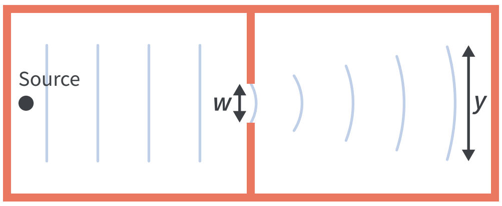
The star Aldebaran emits 5.7 × 10^{28} J s^{-1} in the form of electromagnetic radiation as a result of nuclear fusion reactions in the star's core. Calculate the rate of the corresponding loss in the star's mass.

Adapted from 2017 VCAA Exam Section A Q11

Key science skills

Question 15 (4 MARKS)

Michael is creating plane waves in a ripple tank. He inserts a wall with a gap to observe how the width of the diffraction pattern, y, is affected by the size of the gap, w.



a Identify the independent, dependent, and controlled variables. (3 MARKS)

b Nora follows the same method as Michael and records very similar results. What does this suggest about the experiment and its results? (1 MARK)

CHAPTER 9 QUESTIONS

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

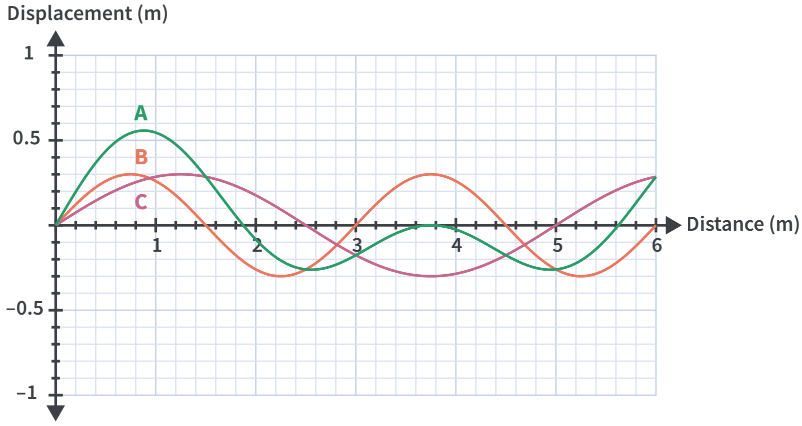
TOTAL MARKS: 50

SECTION A

All questions in this section are worth one mark.

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

Use the following graph to answer Questions 1 and 2.



Question 1

Which wave results from the superposition of the other two waves?

A Green wave

B Orange wave

C Purple wave

D None of the waves result from superposition of the other waves.

Question 2

Which option correctly identifies the properties of the orange wave (B)?

A Wavelength = 6 m, amplitude = 0.3 m, frequency = 3 Hz

B Wavelength = 3 m, amplitude = 0.3 m, frequency = 0.33 Hz

C Wavelength = 3 m, amplitude = 0.25 m, frequency = 3 Hz

D Wavelength = 3 m, amplitude = 0.3 m, frequency unknown

Question 3

Which concept is **not** involved in the formation of a standing wave?

A Reflection

B Diffraction

C Superposition

D Interference

Question 4

For which of the following wavelengths would a given point that is 1.0 m from one wave source and 2.0 m from another coherent wave source correspond to a node?

A 10 cm

B 20 cm

C 30 cm

D 40 cm

Question 5

Gareth is standing next to the Melbourne Grand Prix track. Which of the following describes the engine sound that Gareth hears as a result of a race car's movement as the car approaches and then drives away from him?

A A louder sound while the car is moving towards him and a softer sound while the car is moving away from him

B A softer sound while the car is moving towards him and a louder sound while the car is moving away from him

C A higher frequency sound while the car is moving towards him and a lower frequency sound while the car is moving away from him

D A lower frequency sound while the car is moving towards him and a higher frequency sound while the car is moving away from him

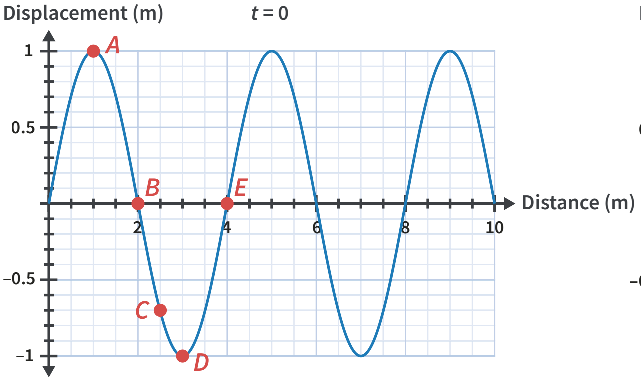
SECTION B

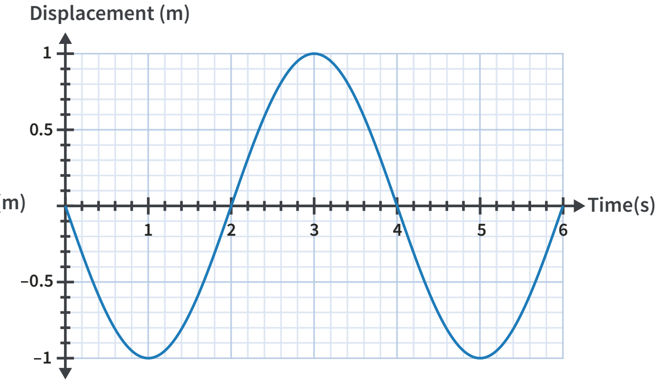
In questions where more than one mark is available, appropriate working must be shown.

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

Question 6 (8 MARKS)

The two graphs represent the characteristics of the same transverse wave travelling along a rope. The displacement-distance graph depicts the rope at $t = 0$ s. The displacement-time graph represents a single particle on the rope.





a Calculate the speed of the wave. (2 MARKS)

b In which direction (up, down, left, or right) is particle *C* moving at the instant shown? (1 MARK)

c Which particle (*A*, *B*, *C*, *D* or *E*) could the displacement-time graph represent? (1 MARK)

d Draw the displacement-distance graph at $t = 1.0$ s. (2 MARKS)

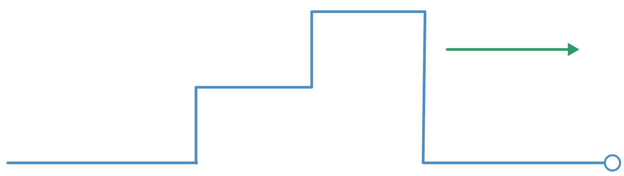
e Draw the displacement-time graph for particle *A* between $t = 0$ and $t = 6.0$ s. (2 MARKS)

Question 7 (2 MARKS)

Draw the following wave pulse after reflection from

a a free end. (1 MARK)

b a fixed end. (1 MARK)



Question 8 (5 MARKS)

Two speakers are used at a school assembly. Take the speed of sound in air as 340 m s^{-1}.

a Two humanities teachers setting up the assembly are discussing the effect of using two speakers rather than one. Mr Ridley suggests that all students in the hall will hear the sound to be twice as loud, while Ms Hawes believes the volume will depend on the students' position. Evaluate the two opinions with reference to the relevant theory. (2 MARKS)

b Two troublesome friends have been separated for assembly. Toby sits 5.0 m from one speaker and 8.4 m from the other. Reginald sits 1.0 m from one speaker and 2.7 m from the other. Use calculations to compare the sound heard by each student when both speakers emit a 100 Hz coherent sound. (3 MARKS)

Question 9 (5 MARKS)

Waves travel along a 5.0 m long string at 28 m s^{-1}. Both ends of the string are fixed.

a Determine the longest wavelength standing waves possible on such a string. (1 MARK)

b Calculate the third lowest frequency standing waves possible on such a string. (2 MARKS)

c Calculate the third lowest frequency standing waves possible on such a string if one end is now free. (2 MARKS)

Question 10 (2 MARKS)

Explain the difference between standing waves that form on a string with two fixed ends compared to a string with one fixed end.

Question 11 (5 MARKS)

Andrew and Missy are studying a variety of wave phenomena using variable wave sources and a wave receiver.

a Two coherent sources emit waves in all directions. A wave receiver is placed within range of the sources however the receiver does not register any incoming waves. Explain how this is possible. (1 MARK)

b Andrew and Missy now observe the diffraction pattern of waves from a single source passing through a gap. Explain what will happen to the diffraction pattern as they decrease the frequency emitted by the source. (2 MARKS)

Diagram relates to part b

c The students set up a new experiment where the wave receiver moves away from the wave source. What will be the effect on the detected frequency, compared to if the receiver was stationary? Identify the relevant physics principle. (2 MARKS)

Question 12 (4 MARKS)

Water waves are being created in a swimming pool. The waves have a period of 1.50 s and a wavelength of 9.00 m.

a Calculate the speed of the waves. (1 MARK)

b Water waves with the same properties are now produced by two coherent sources, *A* and *B*. Point *P* is located on the second nodal line 12.0 m away from source *A*. Calculate the distance from source *B* to the point *P*. (3 MARKS)

Question 13 (4 MARKS)

A string with one fixed end and one free end forms a 5th harmonic standing wave with a frequency of 30 Hz. The wave speed on the string is 6.0 m s^{-1}.

a Draw a diagram of the standing wave. (2 MARKS)

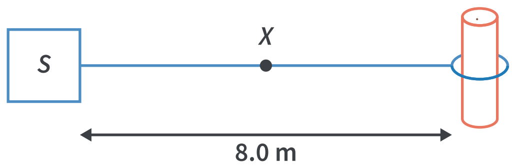
b Calculate the length of the string. (2 MARKS)

Question 14 (2 MARKS)

Students set up a fourth harmonic standing wave on a 1.40 m string with a frequency of 250 Hz and an amplitude of 6 cm. Calculate the speed of the wave on the string.

Question 15 (5 MARKS)

Waves with wavelength 2.0 m are being generated by a source *S* on an 8.0 m string with one fixed end and one free end.



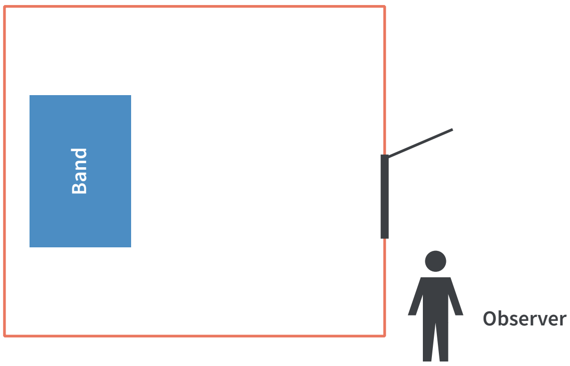
a Will a standing wave form in this situation? Explain your answer. (2 MARKS)

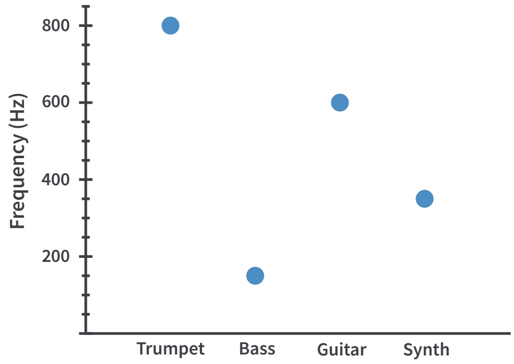
b What type of interference occurs between the original travelling wave and the reflection at point *X*, halfway along the string? (3 MARKS)

Question 16 (3 MARKS)

A rock band is playing in a soundproof room but with an open door. An observer stands outside the room with the wall in between her and the band.

The graph shows the mean frequency of sound produced by the four instruments in a rock band. Assume all instruments are producing the same volume.





a Why it is possible for the observer to hear the instruments despite the soundproof wall in between? (1 MARK)

b Which instrument will the observer be least likely to hear? Justify your answer. (2 MARKS)

UNIT 4 AOS 1, CHAPTER 10

Light behaving as a wave

10

Key knowledge

- describe light as an electromagnetic wave which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, c, in a vacuum
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, x-ray and gamma, and identify the distinct uses each has in society
- explain polarisation of visible light and its relation to a transverse wave model
- investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ and $n_1v_1 = n_2v_2$
  - total internal reflection and critical angle including applications: $n_1\sin(\theta_c) = n_2\sin(90°)$
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another
- explain the results of Young's double slit experiment with reference to:
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n-\frac{1}{2}\right)\lambda$ respectively
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$

Image: Anna Om/Shutterstock.com

10A ELECTROMAGNETIC WAVES

This lesson introduces the concept of light as an electromagnetic wave and discusses the features and uses of the electromagnetic spectrum. We will explore the wave nature of light throughout the rest of Chapter 10.

10A Electromagnetic waves	10B Refraction and reflection	10C Polarisation and colour dispersion	10D Young's double slit experiment

Study design key knowledge dot points

- describe light as an electromagnetic wave which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, *c*, in a vacuum
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, x-ray and gamma, and identify the distinct uses each has in society

Key knowledge units

Light as an electromagnetic wave	4.1.10.1 & 4.1.11.1
The electromagnetic spectrum	4.1.12.1

Formulas for this lesson

Previous lessons	New formulas
9B * $v = f\lambda$	No new formulas in this lesson

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

electromagnetic spectrum the range of all possible electromagnetic waves ordered by frequency or wavelength

electromagnetic wave a transverse wave comprised of changing electric fields and perpendicular changing magnetic fields produced by the acceleration of charged particles. Unlike a mechanical wave, it does not require a medium

Light as an electromagnetic wave 4.1.10.1 & 4.1.11.1

OVERVIEW

Light can be modelled as an electromagnetic wave comprised of changing perpendicular electric and magnetic fields. It is produced by the acceleration of charged particles. The speed of 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 changes. A changing electric field produces a perpendicular changing magnetic field, and the changing magnetic field likewise produces a changing electric field. This is known as an electromagnetic wave or electromagnetic radiation. An accelerating charged particle will therefore emit electromagnetic waves. If the charged particle is oscillating, the frequency of the electromagnetic wave will be equal to the frequency of the oscillation. Visible light consists of a small range of frequencies of electromagnetic waves.

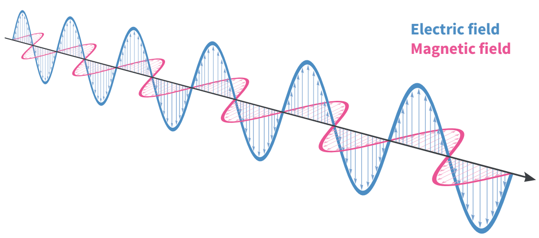


Image: Fouad A. Saad/Shutterstock.com

Figure 1 An electromagnetic wave. The changing electric and magnetic fields are perpendicular to each other.

It is important to recognise that, unlike mechanical waves, electromagnetic waves do not require a medium. Whereas mechanical waves exist as the transfer of energy through matter, electromagnetic waves exist as the transfer of energy through the propagation of electric and magnetic fields.

All electromagnetic waves travel at the same speed in a vacuum, independent of frequency and wavelength. As we saw in chapter 4, this speed is denoted by the symbol c which is equal to 3.0×10^8 m s^{-1} to two significant figures.

Electromagnetic waves can be described by the wave equation with c substituted in as the wave's velocity: $c = f\lambda$.

The electromagnetic spectrum 4.1.12.1

OVERVIEW

All possible frequencies of electromagnetic waves comprise the electromagnetic spectrum. The different regions of the electromagnetic spectrum all have valuable uses within society. The visible spectrum is just one of these regions.

THEORY DETAILS

The electromagnetic spectrum is divided into regions defined by their frequency range as shown in Figure 2. Only one small region of this spectrum (wavelengths between ~380 nm and ~750 nm) is visible light. The other regions are invisible to the human eye.

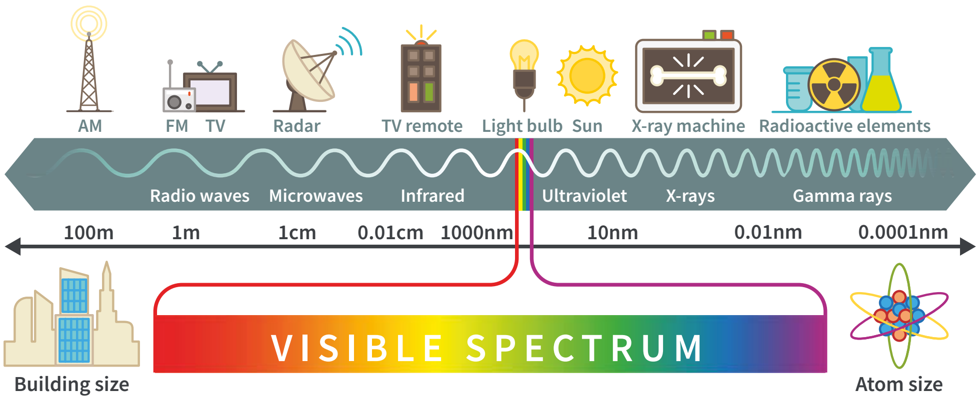


Image: VectorMine/Shutterstock.com

Figure 2 The electromagnetic spectrum. Energy and frequency increases and wavelength decreases from left to right. Red is at the low frequency end of the visible spectrum and violet is at the high frequency end.

The following summarises the properties and uses of the regions of the electromagnetic spectrum in order of **increasing frequency** and energy.

Radio waves

- Travel long distances uninterrupted due to their long wavelength
- Diffract around obstacles like buildings and mountains and can reflect off the ionosphere to help travel long distances
- Mostly used in radio and television communications where they are emitted by radio towers and picked up by antennae on devices such as car radios

Microwaves

- Used to cook food in microwave ovens by matching the resonant frequency of water molecules in food causing them to vibrate
- Also used for mobile phone signals, Wi-Fi and radar systems
- Cosmic microwave background (CMB) radiation is electromagnetic radiation which was created in the early stages of the universe and continues to reach Earth, and provides strong evidence for the Big Bang Theory.

Infrared

- All objects emit electromagnetic radiation due to the thermal vibration of charged particles. At temperatures for which life exists most of this radiation is infrared. For this reason thermal vision goggles use infrared and convert it to visible light to 'see' temperature.
- When infrared radiation hits an object, it causes the particles in that object to vibrate so the object heats up. Radiator heaters and heating lamps use this principle.
- It is also used in some forms of signal transmission such as TV remote controls.

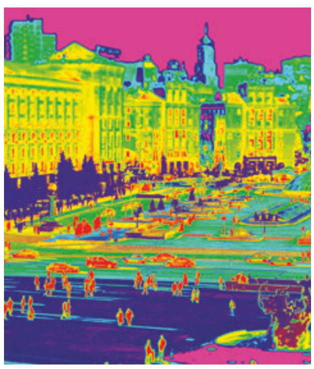


Image: Dezay/Shutterstock.com

Figure 3 A thermal image. Redder colours indicate higher temperatures.

Visible light

- It allows humans (and many species) to see.
- When we see an object as coloured, the object is reflecting the wavelengths of the colour it appears to be and absorbing the complementary (all other) wavelengths.
- Red is at the low frequency/long wavelength end of the visible spectrum and violet is at the high frequency/short wavelength end as shown in Figure 2.

Ultraviolet

- Used in sterilisation processes and to cure (harden) different materials due to its high energy
- Used in black lights (UV light bulbs) for forensic analysis as it causes other substances, including bodily fluids, to fluoresce (emit visible light)
- Produced along with visible light and infrared by the Sun

X-ray

- High energy and highly penetrating
- Useful for imaging bone structures as they pass easily through soft tissue
- Can damage the DNA in cells or even kill cells in significant doses
- Produced by cosmic objects and used by astronomers to study those objects

Image: Puwadol Jaturawutthichai/ Shutterstock.com

Figure 4 A medical x-ray image

Gamma rays

- Higher energy, more penetrating, and more damaging than x-rays
- Produced by nuclear reactions
- Used in medicine to target and kill tumour cells but care must be taken to minimise damage to other cells
- Produced by cosmic objects and used by astronomers to study those objects

Theory summary

- Light is a self propagating electromagnetic wave comprised of perpendicular electric and magnetic fields that is produced by the acceleration of charged particles.
- The speed of light and all electromagnetic waves in a vacuum is 3.0×10^8 m s^{-1}.
- The regions of the electromagnetic spectrum from lowest frequency to highest frequency are radio, microwave, infrared, visible light, ultraviolet, x-ray, and gamma.

KEEN TO INVESTIGATE?

oPhysics 'Electromagnetic Waves' simulation
https://ophysics.com/em3.html

PhET 'Radiating Charge' simulation
https://phet.colorado.edu/en/simulation/legacy/radiating-charge

PhET 'Radio Waves and Electromagnetic Charge' simulation
https://phet.colorado.edu/en/simulation/legacy/radio-waves

YouTube video: CrashCourse – Maxwell's Equations
https://youtu.be/K40lNL3KsJ4

YouTube video: BestOfScience – The Electromagnetic Spectrum
https://youtu.be/cfXzwh3KadE

10A Questions

THEORY REVIEW QUESTIONS

Question 1

The best description of an electromagnetic wave is

A a self propagating longitudinal wave consisting of changing electric and magnetic fields.

B a self propagating transverse wave consisting of changing electric and magnetic fields which can be produced by the acceleration of a charged particle.

C changing electric and magnetic fields resulting in both transverse and longitudinal waves.

D a way to transfer energy through a medium.

Question 2

Which of the following statements about mechanical waves does **not** apply to electromagnetic waves?

A It is a transmission of energy without a net transfer of matter.

B There is an inverse relationship between its frequency and wavelength.

C It requires a medium.

D It can diffract.

Question 3

Which region of the electromagnetic spectrum travels the fastest in a vacuum?

A Gamma rays

B Ultraviolet rays

C Radio waves

D They all travel at the same speed.

Question 4

Which of the following options lists electromagnetic waves in order of **increasing wavelength**?

A Microwave, red light, violet light, ultraviolet, gamma

B Gamma, x-ray, red light, violet light, radio

C Infrared, radio, yellow light, ultraviolet, x-ray

D X-ray, green light, red light, microwave, radio

Question 5

As we progress along the entire electromagnetic spectrum from radio to gamma waves, which option correctly describes the way wavelength, frequency, and energy change?

	Wavelength	Frequency	Energy
A	Decreases	Increases	Increases
B	Increases	Decreases	Increases
C	Increases	Increases	Decreases
D	Decreases	Increases	Decreases

EXAM-STYLE QUESTIONS

This lesson

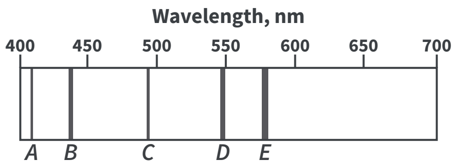
Question 6 (1 MARK)

Order the following regions of the electromagnetic spectrum from longest wavelength to shortest wavelength: orange light, x-rays, microwaves, radio, ultraviolet, infrared.

Question 7 (1 MARK)

Order the following regions of the electromagnetic spectrum from highest energy to lowest energy: red light, radio, ultraviolet, blue light, infrared, gamma.

Question 8 (1 MARK)



The vertical lines in the diagram show the wavelengths of light which a mercury atom can emit (known as an emission spectrum, which will be covered in Chapter 12). The following list gives the five visible colours that are emitted by the mercury atom.

Yellow Green Blue-green Blue Violet

Identify which band (*A*, *B*, *C*, *D* or *E*) represents the green emission.

Adapted from 2018 VCAA Exam Section B Q19a

Question 9 (2 MARKS)

With reference to charged particles, describe how an electromagnetic wave is produced.

Question 10 (3 MARKS)

During the Apollo 11 mission when NASA was communicating with astronauts on the Moon, which is 384 400 km from Earth, there was a time delay in the process of sending radio messages.

a Calculate the time it takes for a radio signal to travel from Earth to the Moon. (1 MARK)

b If the signal has a frequency of 144 MHz, calculate its wavelength. (2 MARKS)

Previous lessons

Question 11 (5 MARKS)

The Sun emits energy in the form of electromagnetic radiation that is produced through nuclear fusion.

a Calculate the decrease in the Sun's mass in one second if the Sun's power is 3.85×10^{26} J s^{-1}. (2 MARKS)

b Given that the mass defect of a single fusion reaction that takes place inside the Sun is 0.0276 u (where 1 u = 1.66×10^{-27} kg), calculate the energy released in one fusion reaction. (2 MARKS)

c Hence, calculate the number of nuclear fusion reactions that take place in the sun each second. (1 MARK)

Question 12 (2 MARKS)

Amy is choosing which kind of generator to use for her cabin. She can choose between an AC generator that has a peak voltage of 325 V or a DC supply of 250 V. With the AC supply, the total resistance of appliances in the cabin is 8.0 Ω. Using the DC supply, the total resistance is 9.0 Ω. Which option will provide the most power?

Adapted from 2012 VCAA Exam 2 Section A AoS 1 Q3

Key science skills

Question 13 (2 MARKS)

Several students take measurements of the wavelength of a laser. The wavelength is cited as 532.0 ± 0.1 nm. The wavelengths they measure are: 532.3 nm, 532.5 nm, 532.1 nm, 531.9 nm and 532.7 nm.

Calculate the average value with an appropriate uncertainty.

10B REFRACTION AND REFLECTION

Have you ever noticed the way a straw in a glass of water appears disjointed or bent? Or the way the surface of water can behave a bit like a mirror? This lesson will explore refraction and reflection as behaviours which are consistent with the wave model of light, and introduce Snell's law to describe the behaviour of waves at boundaries.

10A Electromagnetic waves	10B Refraction and reflection	10C Polarisation and colour dispersion	10D Young's double slit experiment

Study design key knowledge dot point

- investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$
  - total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90°)$

Key knowledge units

Refractive indices	4.1.14.1
Light at boundaries	4.1.14.2
Snell's law	4.1.14.3
Total internal reflection and critical angle	4.1.14.4

Formulas for this lesson

Previous lessons		New formulas
9B	* $v = f\lambda$	$n = \frac{c}{v}$
		* $n_1 v_1 = n_2 v_2$
		* $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$
		$n_1 \sin(\theta_c) = n_2$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

angle of incidence the angle to the normal of a ray approaching a medium boundary

angle of reflection the angle to the normal of a ray reflected by a medium boundary

angle of refraction the angle to the normal of a ray refracted by a medium boundary

critical angle the angle above which total internal reflection occurs

normal an imaginary line perpendicular to the medium boundary at the point of incidence

refraction the change in direction of a wave moving between two media with different refractive indices

refractive index for a given medium, the ratio of the speed of light in a vacuum to the speed of light in that medium

total internal reflection the reflection of all incident light at a boundary between two media

transmission the transfer of wave energy from one wave medium to another wave medium

Refractive indices 4.1.14.1

OVERVIEW

The refractive index of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in that medium. It is always equal to or greater than one.

THEORY DETAILS

The speed of light waves in a medium is determined by how fast the wave's alternating electric and magnetic fields can permeate through that medium. This permeability, or optical density, is dependent on the physical characteristics of the medium and is quantified by the refractive index, n.

$$n = \frac{c}{v}$$

n = refractive index of medium (no units), c = speed of light in a vacuum (3.0×10^8 m s^{-1}), v = speed of light in medium (m s^{-1})

Because the speed of light can never exceed c, the minimum value for a refractive index is one ($n \geq 1$). The speed of light in air is very close to c so $n = 1.00$ to three significant figures in air.

From the definition of refractive index, the refractive indices and speeds of light in two different media can be related mathematically.

$$n_1 v_1 = n_2 v_2$$

n_2 = refractive index of first medium (no units), n_2 = refractive index of second medium (no units), v_1 = speed of light in first medium (m s^{-1}), v_2 = speed of light in second medium (m s^{-1})

1 **Worked example**

Light in a glass prism has a speed of 2.0×10^8 m s^{-1}. The speed of light in water is 1.15 times as fast as light in the prism.

a **Calculate the refractive index of the prism.**

b **Calculate the refractive index of water.**

a $n_{prism} = \frac{c}{v_{prism}} = \frac{3.0 \times 10^8}{2.0 \times 10^8} = 1.5$

b $n_1 v_1 = n_2 v_2 \;\therefore n_{prism} v_{prism} = n_{water} v_{water}$

$1.5 \times 2.0 \times 10^8 = n_{water} \times 1.15 \times 2.0 \times 10^8$

$n_{water} = 1.3$

Light at boundaries 4.1.14.2

OVERVIEW

When light reaches a boundary between two media with different refractive indices, some of the light will be reflected and some will be transmitted. The transmitted light will change direction if it is incident at an angle to the normal. This is called 'refraction', and is due to the change in speed between media.

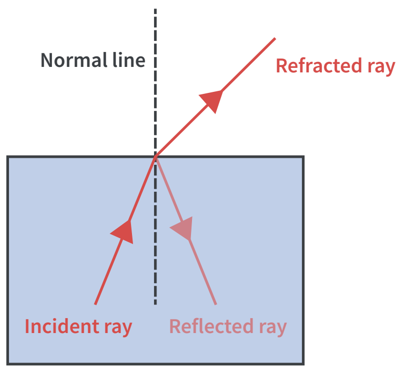


Figure 1 The incident, reflected and refracted light rays at a boundary between media with different refractive indices

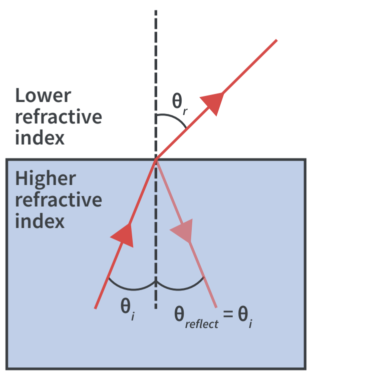


Figure 2 The angle of incidence, angle of reflection (which is equal to angle of incidence) and the angle of refraction at a boundary between media. In this case $\theta_r > \theta_i$ because the light is entering a lower refractive index from a higher refractive index.

THEORY DETAILS

Just like mechanical waves, whenever light hits the boundary between two media some of the light will be reflected. In most scenarios, transmission of light will also occur across the boundary, with some of the wave's energy moving into the new medium.

If light hits a boundary at an angle to the normal (a line perpendicular to the boundary) the change in wave speed will cause the light to change direction. This change of direction is known as refraction.

Light entering a lower refractive index (faster) medium will refract away from the normal, while light entering a higher refractive index (slower) medium will refract towards the normal. No change in direction occurs when the media have the same refractive index. Light rays are always reflected at the same angle as they were incident. It is useful to define the rays of light at a boundary by their angles.

Snell's law 4.1.14.3

OVERVIEW

Snell's law relates the refractive indices in two media to the angle of incidence and angle of refraction.

THEORY DETAILS

When light crosses a boundary from one medium to another it bends either towards or away from the normal, depending on whether it has passed into a medium with a higher or lower refractive index. The angle of refraction is related to the incident angle and the refractive indices of the boundary media by Snell's law:

$$n_1\sin(\theta_1) = n_2\sin(\theta_2)$$

n_1 = refractive index of first medium (no units), n_2 = refractive index of second medium (no units), θ_1 = angle to the normal in first medium (°), θ_2 = angle to the normal in second medium (°)

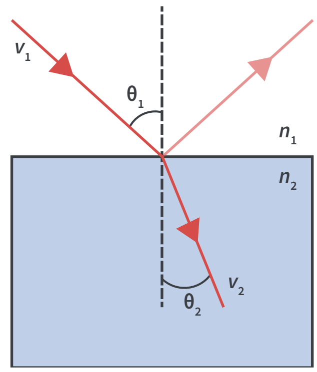


Figure 3 The variables related by Snell's law at a boundary between two media

2 Worked example

A ray of light passes from air ($n = 1.00$) to water ($n = 1.33$). If the incident angle of the ray is 43.0°, calculate the angle of refraction.

We know Snell's law relates these four variables: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$

n_1 is the refractive index of the first medium (air) $\therefore n_1 = 1.00$

n_2 is the refractive index of the second medium (water) $\therefore n_2 = 1.33$

θ_1 is the incident angle $\therefore \theta_1 = 43.0°$

Substitute in known values: $1.00 \times \sin(43°) = 1.33 \times \sin(\theta_2)$

Rearrange for the unknown value: $\theta_2 = \sin^{-1}\left(\frac{1.00 \times \sin(43.0°)}{1.33}\right) = 30.8°$

The angle of refraction is 30.8°.

Total internal reflection and critical angle 4.1.14.4

OVERVIEW

When light is refracted away from the normal, the incident angle can be increased to the point where the angle of refraction reaches 90°. The angle of incidence for which this occurs is called the critical angle. Light with an incident angle greater than this angle will be totally internally reflected.

THEORY DETAILS

When light travels from a **higher to a lower refractive index** (slower to faster) medium, it bends away from the normal. As a result, the angle of refraction will reach 90° before the incident angle does. The incident angle at which the refracted angle is 90° is called the critical angle.

Once the incident angle is such that the angle of refraction would exceed 90°, light is no longer transmitted across the media boundary: it is totally internally reflected. This can only occur when light moves from a higher to a lower refractive index.

When determining if total internal reflection occurs we must find the critical angle at the medium boundary. We know that when $\theta_1 = \theta_c$, $\theta_2 = 90°$. Substituting these values into Snell's law gives:

$$n_1\sin(\theta_c) = n_2\sin(90°)$$

Now, given $\sin(90°) = 1$:

$$n_1\sin(\theta_c) = n_2$$

n_1 = refractive index of first medium (no units),

n_2 = refractive index of second medium (no units), θ_c = critical angle between the media (°)

Rearranging for θ_c:

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Total internal reflection occurs when $\theta_i > \theta_c$.

Total internal reflection is utilised in telecommunications by using optical fibres, which totally internally reflect light through the length of the fibre. Fibres are often surrounded by a protective, transparent 'cladding' for use, which has a lower refractive index than the fibre.

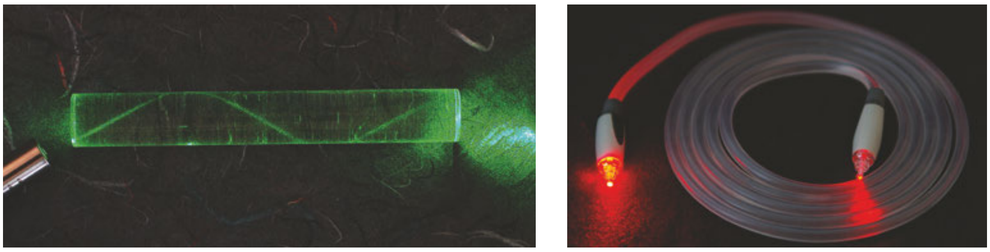


Figure 5 Total internal reflection in a glass rod and the use of total internal reflection to transfer a light signal from one end of an optical fibre to another

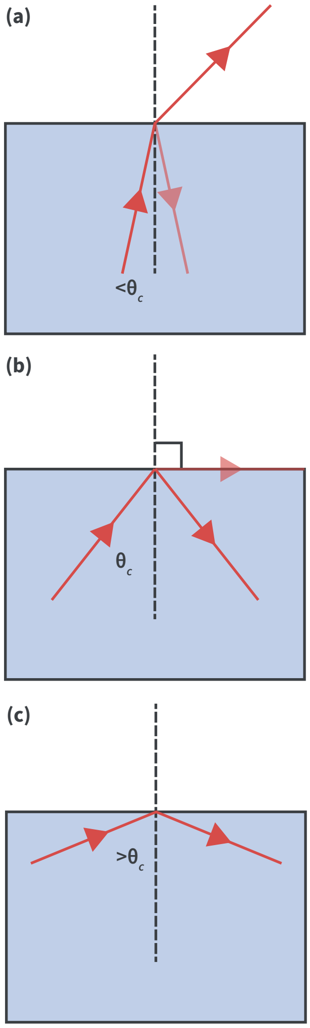


Figure 4 The resultant rays from an incident ray at **(a)** less than, **(b)** equal to, and **(c)** greater than the critical angle passing from a higher to a lower refractive index medium.

Theory summary

- Refractive index is the ratio of speed of light in a vacuum to speed of light in a medium.
- At a medium boundary, light always reflects and can also be transmitted.
- The angle of reflection equals the angle of incidence.
- Transmitted light refracts if incident light hits the boundary at an angle.
- Refraction is away from the normal when moving to a lower refractive index and towards the normal when moving to a higher refractive index.
- Snell's law mathematically describes the direction of waves at a boundary.
- When the angle of incidence is the critical angle, the angle of refraction is 90°.
- Above the critical angle, total internal reflection occurs and no light is transmitted.
- Total internal reflection can only occur when passing from a higher to a lower refractive medium.

KEEN TO INVESTIGATE?

oPhysics 'Reflection and Refraction' simulation
https://ophysics.com/l7.html

PHet 'Bending Light' simulation
https://phet.colorado.edu/en/simulation/bending-light

10B Questions

THEORY REVIEW QUESTIONS

Question 1

Which is the best description of the conditions required for light to reflect?

A Whenever light hits a shiny surface, such as a mirror

B Whenever light passes from a lower refractive index to a higher refractive index material

C Whenever light passes from a higher refractive index to a lower refractive index material

D Whenever light reaches the boundary between two different media

Question 2

Which statement is correct?

A Light bends towards the normal whenever it enters a medium with a high refractive index.

B Light bends away from the normal whenever it enters a medium with a high refractive index.

C Light bends towards the normal whenever it passes from a lower refractive index medium to a higher refractive index medium.

D Light bends towards the normal whenever it passes from a higher refractive index medium to a lower refractive index medium.

Question 3

Higher refractive indices correspond to

A lower speeds of light and $n = 1$ is the highest value refractive index.

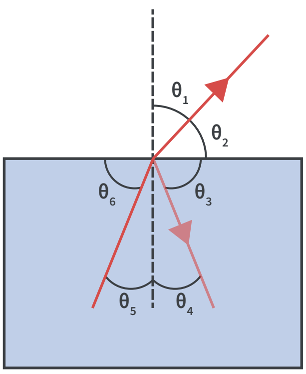
B higher speeds of light and $n = 1$ is the highest value refractive index.

C lower speeds of light and $n = 0$ is the lowest value refractive index.

D lower speeds of light and $n = 1$ is the lowest value refractive index.

Question 4

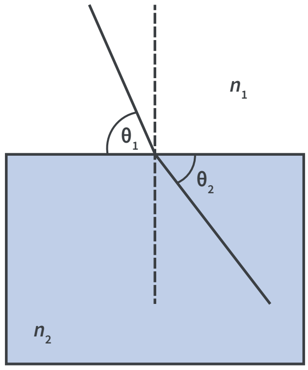
Which option correctly identifies the angles of incidence, reflection and refraction in the diagram?



	Angle of incidence	Angle of reflection	Angle of refraction
A	θ_1	θ_2	θ_3
B	θ_5	θ_4	θ_1
C	θ_6	θ_3	θ_2
D	θ_5	θ_4	θ_2

Question 5

Which of the following relationships between the four labelled variables is correct?



A $n_1\sin(\theta_1) = n_2\sin(\theta_2)$

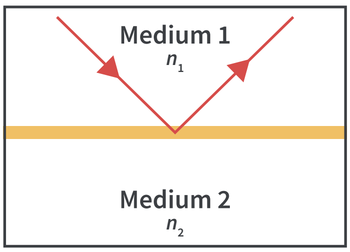
B $n_2\sin(\theta_1) = n_1\sin(\theta_2)$

C $n_1\sin(90 - \theta_1) = n_2\sin(90 - \theta_2)$

D $n_2\sin(90 - \theta_1) = n_1\sin(90 - \theta_2)$

Question 6

Which of the following conditions must be met for total internal reflection to occur in medium 1 when light hits the boundary between medium 1 and 2?



A $n_1 > n_2$

B $n_1 = n_2$

C $n_1 < n_2$

D No condition has to be met.

EXAM-STYLE QUESTIONS

This lesson

Question 7 (1 MARK)

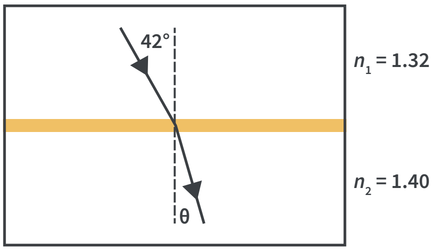
The refractive index of polycarbonate is 1.60. Calculate the speed of light in polycarbonate.

Question 8 (2 MARKS)

A ray of light passes through the boundary between air ($n = 1.00$) and glass. The incident and refracted angles are 45.0° and 30.0°, respectively. Calculate the refractive index of the glass.

Question 9 (2 MARKS)

A ray of light is observed to bend when passing between two transparent liquids. Calculate the angle of refraction of the ray if it has an incident angle of 42°.

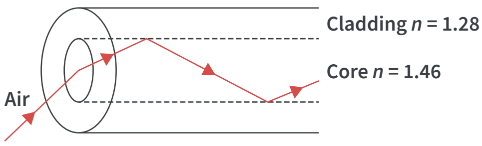


Question 10 (3 MARKS)

The wavelength and frequency of a light wave in saltwater are 540 nm and 4.085×10^{14} Hz. Calculate the refractive index of saltwater.

Question 11 (2 MARKS)

An optical fibre has a core refractive index of 1.46 and a cladding with a refractive index of 1.28. Calculate the critical angle inside the optical fibre.

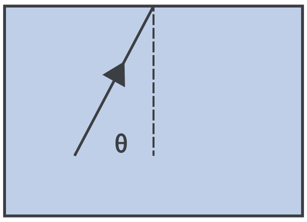


Adapted from 2018 VCAA Exam Section B Q12

Question 12 (2 MARKS)

The desired critical angle for an optical fibre with $n_{core} = 1.7$ is 48°. What refractive index would the cladding of the fibre need in order to achieve this critical angle?

Question 13 (3 MARKS)



Copy the diagram and draw the rays reflected or refracted when the incident angle of the ray in the figure is

a slightly greater than the critical angle. (1 MARK)

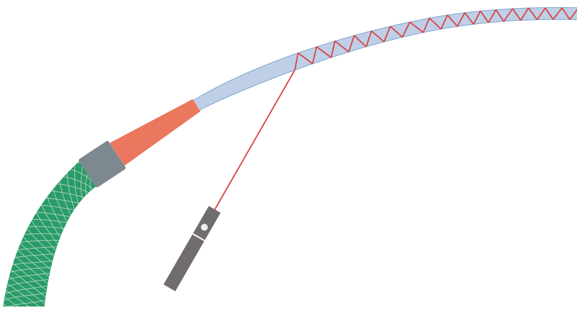
b slightly less than the critical angle. (2 MARKS)

Question 14 (3 MARKS)

The speed of a ray of light passing between two media with unknown refractive indices increases by a factor of 1.2. If the ray of light has a refracted angle of 60°, what is the incident angle?

Question 15 (2 MARKS)

A laser light passes into and is then guided by the stream of a hose. Explain how it is possible for the stream to guide the light.

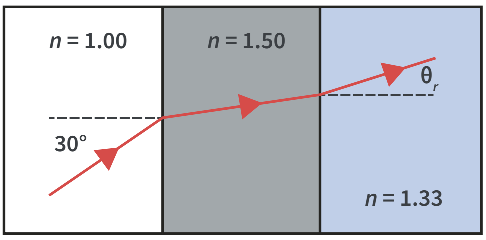


Question 16 (2 MARKS)

A glass fibre has a critical angle of 50° in air. Will total internal reflection still be possible inside the fibre if it is placed in a tub of water with $n = 1.33$? Assume the refractive index of air is 1.00.

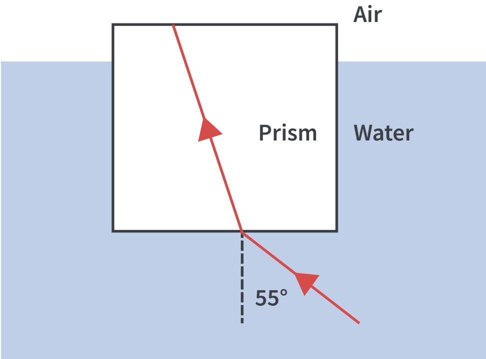
Question 17 (3 MARKS)

A light ray passes from air ($n = 1.00$) into a glass cube ($n = 1.50$) and then into a liquid ($n = 1.33$). The boundaries between the media are parallel. Calculate the magnitude (in degrees) of the difference between the initial incident angle of 30° and the final refracted angle.



Question 18 (4 MARKS)

A cubic prism is floating in water and has a refractive index such that $v_{prism} = 0.80 \times v_{water}$ and $v_{prism} = 0.60 \times v_{air}$. A light ray from the water hits the prism at 55° to the normal. Determine whether the ray will be totally internally reflected the next time it reaches a boundary, assuming the next boundary is on the opposite face of the prism. Do not assume values for the refractive indices of air or water.



Previous lessons

Question 19 (2 MARKS)

a Draw field lines for the gravitational field created by a stationary spherical object with uniform mass density. Use eight lines. (1 MARK)

b Draw field lines for the electric field created by a stationary spherical object with uniform positive charge. Use eight lines. (1 MARK)

Question 20 (5 MARKS)

Step-up and step-down transformers are used between a power source and load to reduce power loss. The transmission wires have a total resistance of 9.00 Ω and carry an 8.00 A_{RMS} current.

a What is the power loss in the transmission wires? (1 MARK)

b The step-up transformer takes an input voltage of 240 V_{RMS} and outputs 200 kV_{peak}. Determine the turns ratio, $N_{out} : N_{in}$, of this transformer to three significant figures. (2 MARKS)

c The step-up transformer is changed so that it steps up to 50 kV_{peak} instead of 200 kV_{peak}. By what factor would the power loss in the transmission lines increase? (2 MARKS)

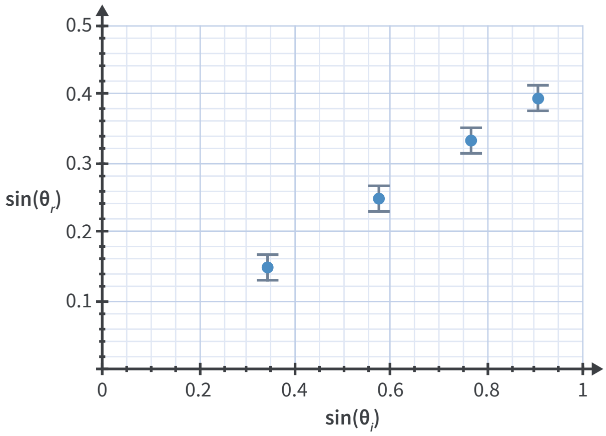
Key science skills

Question 21 (7 MARKS)

A scientist is analysing the diamond engagement ring given to them by their fiancé. They alter the incident angle of a 540 nm green laser light and record the refracted angle after it moves from air (n = 1.00) into the diamond. Real diamonds have refractive indices above 2.80.

a What are the dependent and independent variables in this experiment? Also name one controlled variable in this experiment. (3 MARKS)

b The scientist plots the results. Calculate the gradient of the line of best fit. (2 MARKS)



c Use the value of the gradient to determine whether the diamond analysed is real. (2 MARKS)

10C POLARISATION AND COLOUR DISPERSION

This lesson will introduce the polarisation of light, how polarisation can be achieved, and why the ability to polarise light supports the transverse wave model of light. The lesson will also explore how white light can be dispersed into separate colours.

10A Electromagnetic waves	10B Refraction and reflection	10C Polarisation and colour dispersion	10D Young's double slit experiment

Study design key knowledge dot points

- explain polarisation of visible light and its relation to a transverse wave model
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another

Key knowledge units

Polarisation	4.1.13.1
White light and colour dispersion	4.1.15.1

No previous or new formulas for this lesson

Definitions for this lesson

dispersion the separation of white light into its constituent colours due to the different refractive indices for different frequencies (colours) of light in a given medium

plane a flat, two-dimensional space

polarised wave a transverse wave whose oscillations exist in only one plane

polarising filter a material which polarises light in the direction of the filter's transmission axis

Polarisation 4.1.13.1

OVERVIEW

The polarisation of light is dependent on light being a transverse wave. Polarisation restricts the direction of wave oscillations to one plane.

THEORY DETAILS

The oscillations of a travelling transverse wave, such as light, can be in any plane that is perpendicular to the direction of wave travel. When a transverse wave is polarised, the oscillations occur in only a single perpendicular plane.

Light can be polarised by polarising filters (made of materials known as polaroids) or by reflection off non-metallic surfaces. The polarisation direction of light is the direction of oscillations in the electric field. The observation that light can be polarised supports the model that light is a transverse wave because polarisation is solely a property of transverse waves. Longitudinal waves cannot be polarised as their oscillations are only in the direction of wave travel.

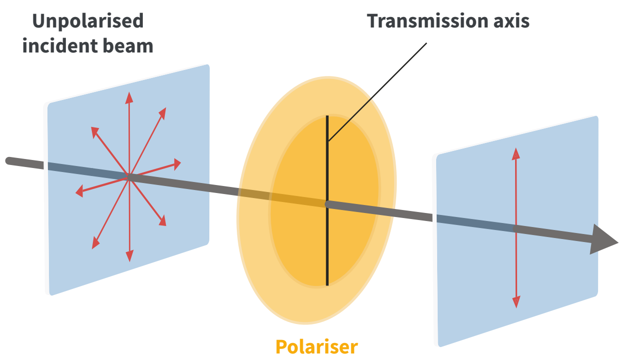


Figure 1 Transverse light waves originally unpolarised are polarised in the direction of the transmission axis of a polarising filter. The arrows indicate the direction of electric field oscillation.

Polarising filters will:

- polarise light in a single plane.
- block light that is already polarised in a perpendicular direction to the filter's transmission axis.
- not alter light that is already polarised in the filter's transmission axis.
- transmit the parallel component of light that is already polarised at an angle (but not perpendicular) to the filter's transmission axis.

A common scenario where it is useful to polarise light is when looking at reflective surfaces such as oceans, lakes, snow, and windows. A polarising filter such as polarised sunglasses can be used to minimise the reflections seen from the surface.

Figure 2 A comparison of viewing the surface of water without (left) and with (right) a polarising filter. The filter blocks the reflections from the water, which were polarised in a different direction to the filter.

White light and colour dispersion 4.1.15.1

OVERVIEW

White light is made up of a continuous spectrum of the visible wavelengths of light. The colours within white light are refracted at different angles by refractive media, so they disperse when white light is shone through a prism or lens.

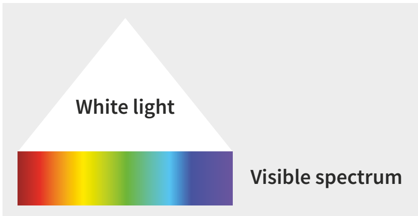


Figure 3 The continuous spectrum of visible light forming what is perceived as white light

THEORY DETAILS

White light is not a particular colour or wavelength of light, but a combination of the continuous visible spectrum of electromagnetic radiation. This spectrum, when viewed all together, is perceived as white light.

The refractive index of a material depends on the wavelength (and therefore colour) of light passing through the material. This means different colours of light are refracted by different amounts through a refracting medium. Mathematically, this difference can be calculated by Snell's law. When each colour component of white light exits the medium, the spectrum has been separated and the component colours are visible.

Consider red and violet waves passing through a prism as these colours are the extremes of the visible spectrum (Figure 4). The refractive index of the prism is higher for shorter wavelengths (like violet) than longer wavelengths (like red), so the prism refracts the violet light more than the red light at both of the material interfaces. When white light is shone onto the prism, this effect is seen across the whole spectrum.

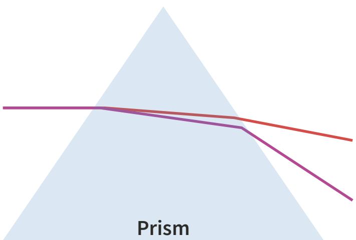


Figure 4 Red and violet waves being refracted through different angles by a prism

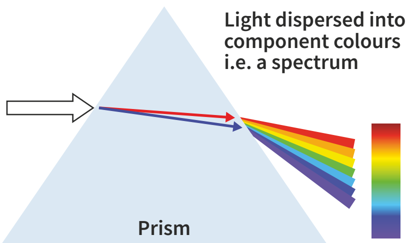


Figure 5 White light being dispersed into its component colours as each colour is refracted through different angles by the prism

Lenses also disperse white light into a spectrum. This is an important factor to consider when designing the lenses used in scientific instruments and cameras.

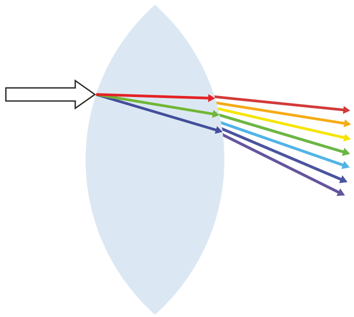


Figure 6 White light being dispersed into its component colours as each colour is refracted through different angles by a convex lens

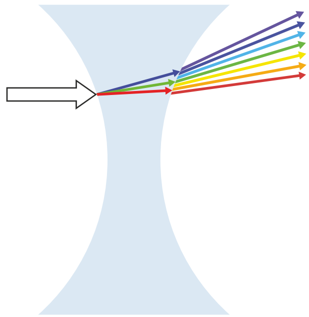


Figure 7 White light being dispersed into its component colours as each colour is refracted through different angles by a concave lens

Theory summary

- Only transverse waves can be polarised.
- Light is polarised by polarising filters or reflection off non-metallic surfaces.
- The ability of light to be polarised is evidence that light can be modelled as a transverse wave.
- Polarising filters block waves already polarised in a perpendicular direction.
- White light is made up of the spectrum of visible light.
- Because the refractive index is dependent on wavelength, white light can be dispersed into its constituent colours by lenses and prisms.

KEEN TO INVESTIGATE?

oPhysics 'Polarization of Light' simulation
https://ophysics.com/l3.html

oPhysics 'Dispersion of Light' simulation
https://ophysics.com/l8.html

oPhysics 'Lenses and Chromatic Aberration' simulation
https://ophysics.com/l15.html

PhET 'Bending Light' simulation
https://phet.colorado.edu/en/simulation/bending-light

10C Questions

THEORY REVIEW QUESTIONS

Question 1

What type of waves can be polarised?

A Mechanical waves only

B Transverse waves only

C Longitudinal waves only

D All waves

Question 2

A polarisation filter

A blocks all planes of oscillation except those in the filter direction.

B blocks all planes of oscillation except those perpendicular to the filter direction.

C blocks all planes of oscillation.

D blocks all waves except longitudinal waves.

Question 3

White light is

A a single wavelength of light.

B visible light waves with extremely high intensity.

C the full, continuous electromagnetic spectrum.

D a continuous spectrum of visible light.

Question 4

The dispersion of white light by a prism or lens is due to

A the high refractive index of these objects.

B total internal reflection.

C the polarisation of different colours of light.

D the dependence of refractive index on wavelength.

EXAM-STYLE QUESTIONS

This lesson

Question 5 (2 MARKS)

Unpolarised light from a lamp is incident on a surface.

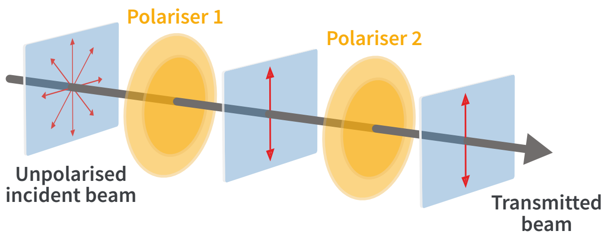
What is the qualitative effect on the intensity of light hitting this surface if a polarising filter is placed between the source and the surface? Explain your answer.

Question 6 (4 MARKS)

Unpolarised light waves pass through two polarising filters as shown.

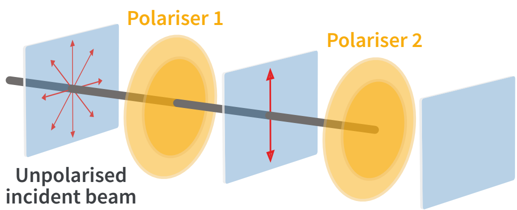
Determine the direction of the transmission axis (horizontal or vertical) of each polarising filter in each case.

a



(2 MARKS)

b



(2 MARKS)

Question 7 (1 MARK)

How does the ability of light to be polarised support the wave model of light?

Question 8 (3 MARKS)

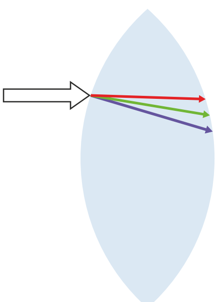
Light inside diamonds is totally internally reflected off multiple surfaces, giving diamonds their famous shine. The shine of diamonds also exhibits multiple colours when only a white light is incident on the diamond.

Explain why diamonds exhibit a colourful shine, justifying your response with relevant theory.

Question 9 (2 MARKS)

The diagram shows red, green, and violet light being shone through a convex lens.

What can be concluded about how the refractive index of the lens changes based on the wavelength of light?



Question 10 (3 MARKS)

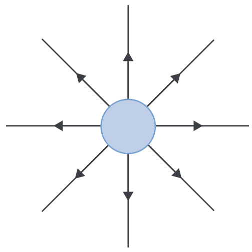
Explain why wearing appropriately polarised sunglasses enables the wearer to more clearly view an object under the surface of a lake.

Previous lessons

Question 11 (2 MARKS)

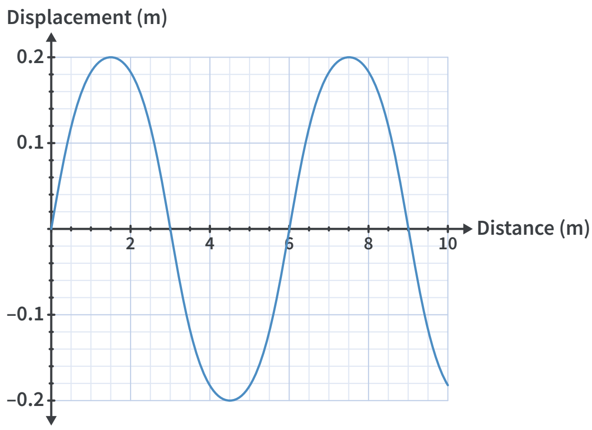
The following diagram represents field lines around a spherical particle of uniform mass density. Could these field lines represent the particle's gravitational field?

Explain why or why not.



Question 12 (2 MARKS)

Determine the amplitude and wavelength of this mechanical wave.



Question 13 (1 MARK)

A string is being plucked at 10 Hz, producing waves of wavelength 0.15 m. What is the period of these waves?

Key science skills

Question 14 (2 MARKS)

Toni Stark is investigating the effect of lens shape on colour dispersion. She shines white light through a glass lens and records the distance between the dispersed red and violet light. She then replaces the glass lens with a plastic lens that has greater curvature, and repeats the measurements. Is this a valid scientific experiment?

Explain why or why not.

Question 15 (2 MARKS)

A student in a well-lit classroom is investigating the effect of a polarising filter where a single wavelength light source passes light through the filter onto a detector. The student records the intensity with and without the filter present, and presents their results to the class.

List one way to reduce the effects of random errors and one way to reduce the effects of systematic errors in this experiment.

10D YOUNG'S DOUBLE SLIT EXPERIMENT

This lesson introduces Young's famous double slit experiment. We will relate our knowledge of diffraction and interference from Chapter 9 to the context of light and show how this supports the wave model of light.

10A Electromagnetic waves	10B Refraction and reflection	10C Polarisation and colour dispersion	10D Young's double slit experiment

Study design key knowledge dot point

- explain the results of Young's double slit experiment with reference to:
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n-\frac{1}{2}\right)\lambda$ respectively
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$

Key knowledge units

Evidence for the wave-like nature of light	4.1.16.1
Fringe spacing	4.1.16.2

Formulas for this lesson

Previous lessons		New formulas
9D	* Constructive: $p.d. = n\lambda$	* $\Delta x = \frac{\lambda L}{d}$
9D	* Destructive: $p.d. = \left(n-\frac{1}{2}\right)\lambda$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

fringe spacing the distance between adjacent bright or dark bands in a double slit interference pattern

Evidence for the wave-like nature of light 4.1.16.1

OVERVIEW

Young's double slit experiment shows light exhibiting the wave properties of diffraction and interference. This challenged the particle nature of light and provided evidence for a wave model of light.

THEORY DETAILS

In 1801, a physicist called Thomas Young performed an experiment in which he shone light through two slits onto a screen and observed alternating bright and dark regions (see Figure 1).

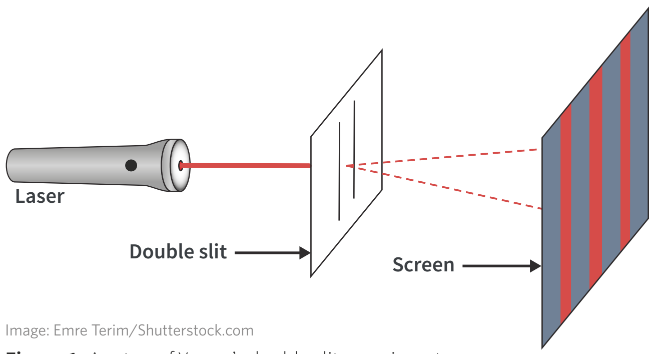


Image: Emre Terim/Shutterstock.com

Figure 1 A setup of Young's double slit experiment

Interference and diffraction of light

The pattern of alternating high and low intensity (bright and dark) regions can be explained as a wave interference pattern (see lesson 9D). Bright bands are caused by **constructive interference** and the dark bands by **destructive interference**.

When the laser is shone through the two slits **diffraction** occurs. This is what we would expect a water wave to do when passing through a gap (see lesson 9G). This allows the slits to be treated as sources of light. The diffracted light from these slits is coherent as it originates from the same source.

Constructive and destructive interference results from the interaction of the diffracted light from the two slits.

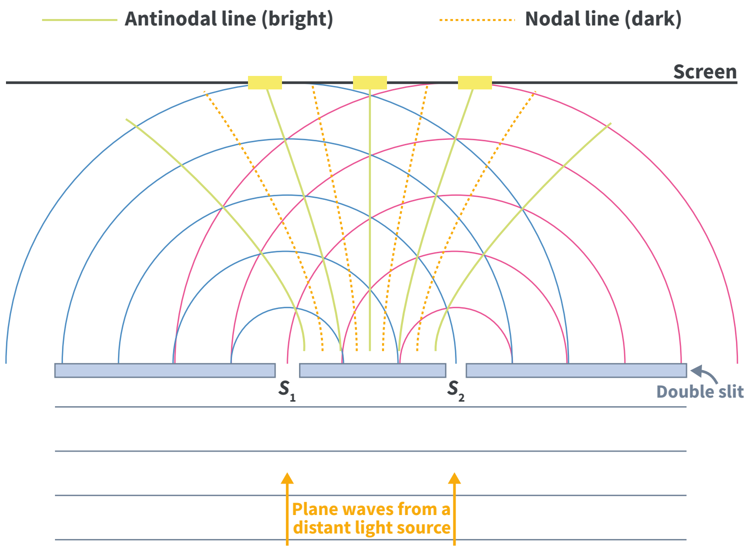
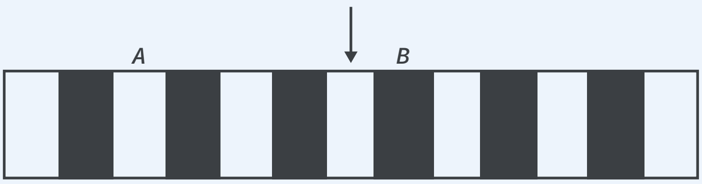


Figure 2 The slits act as sources of light and an interference pattern occurs between the diffracted light from each slit. Antinodal lines lead to bright bands and nodal lines to dark bands.

As the concepts are the same, the process used to answer questions about Young's double slit experiment will be similar to that used for interference patterns in lesson 9D.

1 Worked example



The above diagram represents the pattern observed in a double slit experiment. The arrow indicates the central bright band. The path difference to bright band *A* is 1.2×10^{-6} m.

a **Calculate the wavelength of the light.**

b **Determine the path difference to the dark band *B*.**

a 'Bright' tells us to use the constructive path difference equation.

Band *A* is the 2nd bright band from the centre so $n = 2$ in the equation.

$p.d. = n\lambda \;\therefore 1.2 \times 10^{-6} = 2 \times \lambda$

$\lambda = 6.0 \times 10^{-7}$ m

b 'Dark' tells us to use the destructive path difference equation.

Band *B* is the 1st dark band from the centre so $n = 1$ in the equation.

$p.d. = \left(n - \frac{1}{2}\right)\lambda \;\therefore p.d. = \left(1 - \frac{1}{2}\right) \times 6.0 \times 10^{-7}$

$p.d. = 3.0 \times 10^{-7}$ m

How Young's double slit experiment supports the wave model of light

- Young's double slit experiment results in an interference pattern.
- Interference is a wave behaviour.
- This means light exhibits wave properties. This is evidence for the wave-like nature of light.
- The particle model incorrectly predicts two bright spots on the screen rather than an interference pattern.

Fringe spacing 4.1.16.2

OVERVIEW

The distance between adjacent bright bands in an interference pattern depends on the slit separation, the distance between the slits and the screen, and the wavelength.

THEORY DETAILS

The fringe spacing is the distance between the centre of adjacent bright bands. This is the same as the distance between adjacent dark bands.

The fringe spacing can be calculated by the following relationship.

$$\Delta x = \frac{\lambda L}{d}$$

Δx = fringe spacing (m), λ = wavelength (m), L = distance from slits to screen (m), d = slit separation (m)

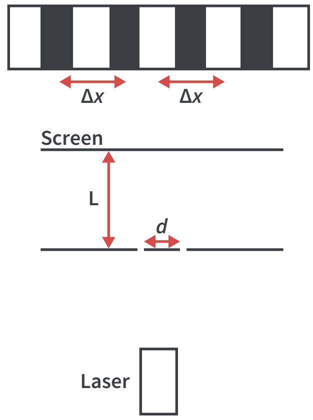


Figure 3 Simplified version of Young's double slit experiment indicating the relevant distances for the fringe spacing equation

Figure 4 Visual representation of the change in variables

2 **Worked example**

A laser with wavelength 600 nm is incident on a sheet with two slits 3.00×10^{-5} m apart. The interference pattern is visible on a screen 1.00 m behind the slits.

a **Calculate the distance between the adjacent bright bands.**

b **Calculate the distance between the central bright band and the dark band to its right.**

a For the fringe spacing equation we have $\lambda = 600$ nm $= 6.00 \times 10^{-7}$ m, $L = 1.00$ m, and $d = 3.00 \times 10^{-5}$ m

$$\Delta x = \frac{\lambda L}{d} = \frac{6.00 \times 10^{-7} \times 1.00}{3.00 \times 10^{-5}} = 2.00 \times 10^{-2} \text{ m}$$

The distance between the adjacent bright bands is 2.00×10^{-2} m.

b The distance between a bright band and the next dark band is half the distance between adjacent bright bands.

$$\Delta x_2 = \frac{2.00 \times 10^{-2}}{2} = 1.00 \times 10^{-2} \text{ m}$$

The distance between the central bright band and the dark band to the right is 1.00×10^{-2} m.

Theory summary

- Young's double slit experiment supports the wave model of light.
- It exhibits the wave property of interference.
- Constructive interference leads to bright bands and destructive interference leads to dark bands. These can be predicted by path difference equations by treating the slits as light sources.
- The fringe spacing, $\Delta x = \frac{\lambda L}{d}$, predicts the distance between the centre of fringes.

KEEN TO INVESTIGATE?

oPhysics 'Double slit diffraction and interference' simulation
https://ophysics.com/l4.html

phET 'Wave interference' simulation
https://phet.colorado.edu/en/simulation/wave-interference

The Open Door Website: Proof of fringe spacing equation
https://www.saburchill.com/physics/chapters2/0014.html

10D Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following options correctly describes Young's double slit experiment?

	Observed result on the screen	Explanation of observed result	Model of light supported
A	Two bright spots	Light travels in straight lines	Wave
B	Alternating bright and dark regions	Interference	Particle
C	Alternating bright and dark regions	Interference	Wave
D	Alternating bright and dark regions	Light travels in straight lines	Particle

Question 2

When constructive interference of light occurs, what can be said about the resultant light at that point?

A The wavelength of the light at the point is greater.

B The frequency of the light at the point is greater.

C The light is less intense (darker).

D The light is more intense (brighter).

Question 3

Given the distances from each slit to the fourth dark band from the centre, which equation is most appropriate to find the wavelength of light in a double slit experiment?

A $p.d. = n\lambda$

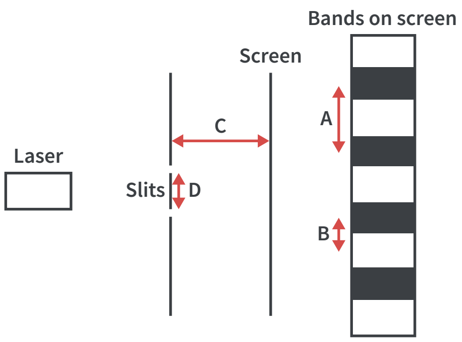
B $p.d. = \left(n - \frac{1}{2}\right)\lambda$

C $\Delta x = \frac{\lambda L}{d}$

D $d = \frac{\lambda L}{\Delta x}$

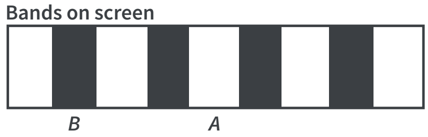
Question 4

Referring to the diagram, which option represents the distance, Δx, in the fringe spacing equation?



Question 5

Which is the correct distance between the points *A* and *B* on the interference pattern shown given that the fringe spacing is 2.00 cm and the wavelength is 576 nm?



A 1.00 cm **B** 3.00 cm **C** 4.00 cm **D** 6.00 cm

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

Which of the following options correctly describes the effect of increasing the slit separation in a double slit experiment?

A The distance between adjacent bright bands will be closer together.

B The central bright band has greater intensity.

C The central bright band has lower intensity.

D The distance between adjacent bright bands will be further apart.

Question 7 (1 MARK)

Which of the following options correctly describes the effect of increasing the frequency of light in a double slit experiment?

A The distance between adjacent bright bands will be closer together.

B The central bright band has greater intensity.

C The central bright band has lower intensity.

D The distance between adjacent bright bands will be further apart.

Question 8 (5 MARKS)

A laser is shining on two slits which produces an interference pattern on a screen. The fourth dark band is 2.40×10^{-6} m further away from one slit than the other.

a Calculate the wavelength of the incident laser. (2 MARKS)

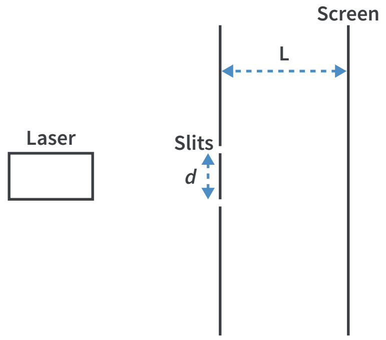
b A different wavelength laser is used and the fourth dark band is now 3.00×10^{-6} m further away from the first slit than the second. Calculate the path difference to the first bright band. (3 MARKS)

Question 9 (2 MARKS)

In a setup of Young's double slit experiment, the sheet behind the slits has a series of alternating dark and bright bands. Explain the existence of these bright and dark bands.

Question 10 (3 MARKS)

Batman and Robin are locked in a cage by the ghost of Thomas Young and have to set up three different double slit experiments with the exact same fringe spacing in order to escape. In each experiment they are given all but one variable which they have to correct. Calculate the unknown values needed to escape.



Δx	λ (nm)	L (m)	d (m)
2.88×10^{-5} m	**a** (1 MARK)	1.50	3.00×10^{-2}
2.88×10^{-5} m	425	**b** (1 MARK)	1.96×10^{-2}
2.88×10^{-5} m	650	2.00	**c** (1 MARK)

Question 11 (3 MARKS)

Two students set up a double slit experiment. Before turning on the laser, Jeffrey claims that a dark spot will occur in the centre of the pattern. Eva disagrees, claiming that the centre is always a bright band.

Evaluate Jeffrey and Eva's opinions. Justify your answer.

Adapted from 2015 VCAA Exam Section A Q17b

Question 12 (3 MARKS)

The centre of the second dark band in a double slit experiment is 9.15×10^{-7} m further from one slit than the other. Find the frequency of the incident light.

Question 13 (3 MARKS)

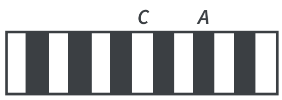
Explain, with reasons, what implications Young's double slit experiment had on understanding the nature of light.

Question 14 (5 MARKS)

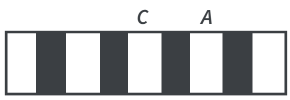
In two experiments, light of different wavelengths is shone through double slits and the interference pattern is recorded. The first experiment used a wavelength of 300 nm.

The pattern for each experiment is shown. Points *A* and *C* are fixed points on the screen.

First experiment



Second experiment



a Another point on the screen to the left of *C* is further from one slit than the other by a distance of 1.50×10^{-7} m. Copy the diagram of the interference pattern for the **first experiment** and identify where this point is by writing the letter *X* above it. (3 MARKS)

b Calculate the wavelength used in the second experiment. (2 MARKS)

Adapted from VCAA 2012 Exam 2 Section A AoS 2 Q2

Question 15 (4 MARKS)

Mr Bean lives 1.20 km from the radio tower for his favourite radio station which has a frequency of 1.00×10^6 Hz. A second radio tower is installed, further from Mr Bean's house, which emits the same frequency. After the installation, Mr Bean stops receiving his favorite channel but can still receive most others.

a Give one reason that Mr Bean's house could no longer be receiving his favourite channel. (1 MARK)

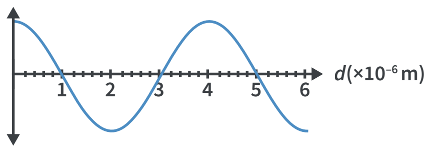
b Mr Bean speaks to the neighbours in his suburb and discovers that, of all the positions where the problem occurs, his house is at the closest position to the midpoint between the towers. How far is his house from the second tower? (3 MARKS)

Previous lessons

Question 16 (2 MARKS)

A craft of mass 20 kg is orbiting Ganymede, Jupiter's largest moon, at an altitude of 400 km. Considering the radius of Ganymede is 2630 km and its mass is 1.48×10^{23} kg, calculate the gravitational force on the craft by Ganymede.

Question 17 (4 MARKS)



In air, light travels at approximately 3.0×10^8 m s^{-1}. In a denser medium, such as water, it travels slower but the frequency does not change. The graph represents the electric field oscillations of a beam of light with a frequency of 5.10×10^{13} Hz travelling through a dense liquid.

a Calculate the speed of light in the medium. (2 MARKS)

b Calculate the refractive index of the liquid. (2 MARKS)

Key science skills

Question 18 (3 MARKS)

In a replication of Young's double slit experiment, a student measures consecutive fringe spacings tabulated here whilst keeping the slit distance and space between the slits and the screen constant.

Wavelength (nm)	Fringe space 1 (10^{-5} m)	Fringe space 2 (10^{-5} m)	Fringe space 3 (10^{-5} m)	Fringe space 4 (10^{-5} m)	Fringe space 5 (10^{-5} m)
450	2.50	2.51	2.51	2.48	2.50
500	7.73	7.74	7.72	7.72	7.73
550	6.18	6.20	6.19	6.21	6.20

a The student states that the results for the 500 nm experiment are most precise. Why is this the case? (1 MARK)

b Use the data and relevant theory to show that systematic errors have affected these results. (2 MARKS)

CHAPTER 10 QUESTIONS

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 gives the order of light from lowest to highest energy?

A Radio, infrared, blue, green, red

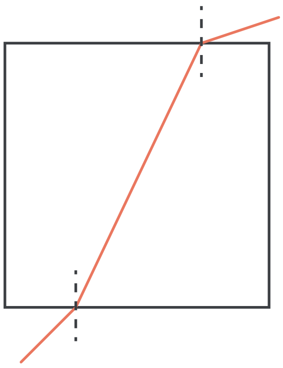
B Red, green, blue, infrared, radio

C Radio, infrared, red, green, blue

D Infrared, radio, red, green, blue

Question 2

A glass prism (n = 1.50) and a bowl of water (n = 1.33) are being used in a refraction experiment. The medium surrounding the experiment is air (n = 1.00). The student conducting the experiment records a diagram of the experiment. What can be concluded about the experimental setup?



A The glass prism is fully submerged in water.

B The glass prism is only surrounded by air.

C The glass prism is partly submerged in water.

D Unable to conclude any of the above statements.

Question 3

Determine which of these wavelengths is not a component of white light.

A Infrared **B** Red **C** Green **D** Blue

Question 4

Polarisation of light suggests that light is behaving as

A any type of wave.

B a particle.

C a longitudinal wave.

D a transverse wave.

Question 5

In a double slit experiment, a student establishes an interference pattern. He then halves the distance between the laser and the slits and doubles the wavelength. Determine the change to the pattern.

A There would be no change to the pattern.

B We can not determine the change as the student changed two variables.

C The fringes would be spaced twice as far apart.

D The fringes would be spaced four times as far apart.

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)

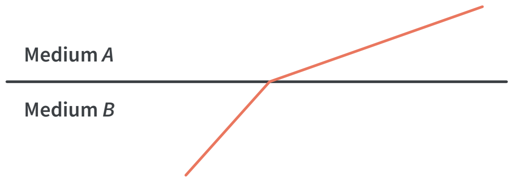
A light-year is the distance light travels in a year and is a common unit of measurement to use when describing astronomical scales. Assuming that an average year has 365 days, convert 0.75 light-years to metres.

Question 7 (2 MARKS)

Describe how light is produced when an electron is accelerated.

Question 8 (1 MARK)

Students observe a light ray moving between media. What can be concluded about the refractive indices of the media?



Question 9 (2 MARKS)

Two media have refractive indices of 1.30 and 1.40. Determine the ratio of the speed in the higher refractive index medium to the speed in the lower refractive index medium. Express your answer in decimal form.

Question 10 (3 MARKS)

The wavelength of a light wave in a medium with $n = 1.80$ is 880 nm. Calculate the frequency of this wave.

Question 11 (2 MARKS)

In a double slit experiment, the third bright band on the screen is 1.50×10^{-6} m closer to one slit than the other. Calculate the wavelength of the light in nanometres.

Question 12 (2 MARKS)

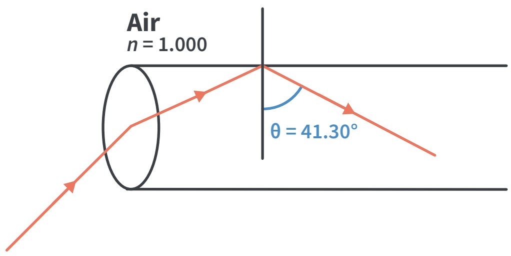
A ray of light is travelling through a prism. It hits the top of the prism at an angle of 78° to the normal. The critical angle of the prism in air is 76°. An observer standing above the prism is shocked that they cannot see the light. Explain how this is possible.

Question 13 (2 MARKS)

Michael argues that regardless of the medium or observer's frame of reference, light will always travel at 3.0×10^{8} m s^{-1}. Evaluate Michael's argument.

Question 14 (6 MARKS)

a Describe the conditions required for total internal reflection to occur. (2 MARKS)



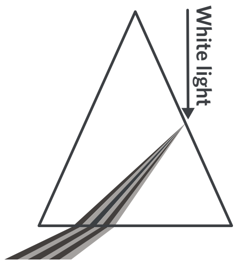
b To transfer information through a fibre optic cable, light beams must travel along the cable without escaping. The minimum angle of incidence along this cable is 41.30°. Which colour(s) can we use to transfer information through this fibre optic cable? Use calculations to support your answer. (3 MARKS)

Colour	Refractive index in fibre optic cable
Red	1.509
Yellow	1.511
Green	1.513
Blue	1.517
Violet	1.521

c If the fibre optic cable was straightened out so no internal reflection occurred, which of the five colours would reach the end of the cable first? (1 MARK)

Question 15 (4 MARKS)

The diagram shows white light being split into its constituent colours by a prism.



a Order the colours below as they would appear from left to right. Justify your answer. (2 MARKS)

green blue yellow red violet orange

b Identify and describe the phenomenon that splits white light into its constituent colours when it travels through a prism. (2 MARKS)

Question 16 (3 MARKS)

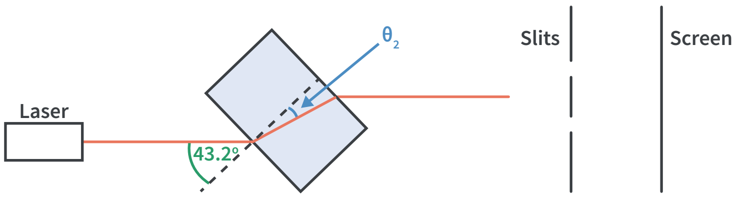
An experiment is conducted where a light source is shone through two polarising filters whose transmission axes are perpendicular to each other.

a If a student was to look through the second polarisation filter, what would they observe? (1 MARK)

b What does the polarisation of light suggest about the nature of light? Explain your answer. (2 MARKS)

Question 17 (5 MARKS)

Superman keeps his super clean super suits in a locked room. The only way to unlock the room is by creating a particular interference pattern using his laser eyes which have a wavelength of 640 nm.

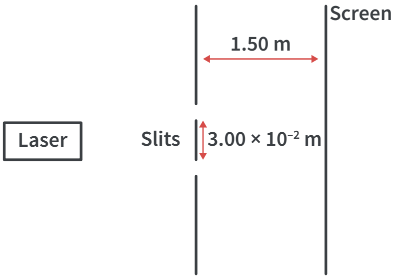


a To make sure the laser does not destroy the lock, it must first pass through a prism which absorbs some of the laser's energy. The angle of incidence when entering the prism is 43.2°, the refractive index of the prism is 1.9, and the refractive index of air is 1.00. Calculate the angle of refraction, θ_2. (2 MARKS)

b To unlock the room, the second dark band from the centre must be 1.60×10^{-6} m further from one slit than the other. Superman shines his laser eyes through the prism and into the lock. Use calculations to determine whether the lock opens. (3 MARKS)

Question 18 (8 MARKS)

In a double slit experiment, the slits are separated by a distance of 3.00×10^{-2} m, the screen is 1.50 m away from the slits, and the laser produces light with a wavelength of 480 nm.

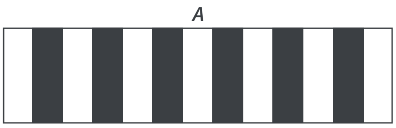


a Calculate the path difference, in metres, to the second bright spot from the centre. (2 MARKS)

b Calculate the fringe spacing. (2 MARKS)

c Describe how the spread of the interference pattern would change if a laser producing 350 nm light is used instead. (1 MARK)

d The diagram shows the interference pattern using the original wavelength. Band *A* is the centre of the pattern. After changing the wavelength of light, would band *A* be a node or antinode? Explain why this is the case. (3 MARKS)



Question 19 (3 MARKS)

Explain how Young's double slit experiment provided evidence for a wave model of light and against a particle model of light.

UNIT 4, AOS 1 QUESTIONS

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 is a possible explanation for observing the sound of a car horn to have a lower pitch than normal?

A The car is further away from the observer than normal.

B The car is closer to the observer than normal.

C The car horn is quieter than normal.

D The observer is moving away from the car.

Question 2

Boris is choosing between 2.4 GHz and 5 GHz frequencies for his Wi-Fi router. He lives in a brick house so the Wi-Fi signal cannot easily pass through the walls. Which of the following options correctly describes a difference between these two frequencies?

A The 5 GHz signal will bend around the corners of the house better.

B The 2.4 GHz signal will bend around the corners of the house better.

C The 5 GHz signal will travel faster.

D The 2.4 GHz signal will travel faster.

Question 3

Which types of waves are able to be polarised?

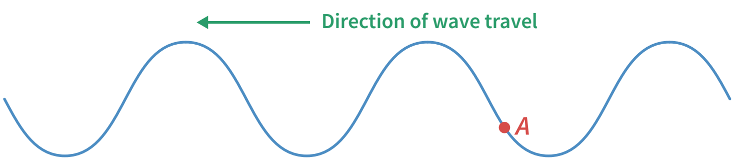
A Longitudinal mechanical waves **and** longitudinal electromagnetic waves.

B Longitudinal electromagnetic waves **and** transverse mechanical waves.

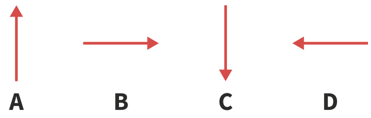
C Transverse electromagnetic waves **and** transverse mechanical waves.

D Transverse electromagnetic waves **and** longitudinal mechanical waves.

Question 4



A string is vibrated to form a travelling wave. Which of the following best gives the direction that point *A* is moving at the instant shown?



Question 5

Which is the best description of the way resonance can occur on a fixed length of string?

A The superposition of a travelling wave with its reflection

B A high enough frequency

C A forced oscillation matching the natural frequency of vibration

D Both A and C

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)

An ambulance is driving towards a pedestrian. Describe the Doppler effect and conclude what the pedestrian would hear when compared with a stationary ambulance.

Question 7 (1 MARK)

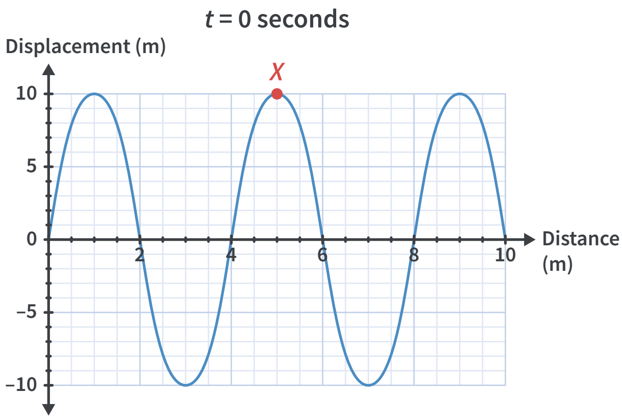
Order the following regions of the electromagnetic spectrum from highest frequency to lowest frequency: microwaves, red light, X-rays, gamma rays, infrared waves, green light.

Adapted from 2017 Sample VCAA Exam Section B Q8

Question 8 (3 MARKS)

A displacement-distance graph at $t = 0$ seconds for a length of rope which has a transverse wave travelling along it is shown. A point halfway along the rope is marked and labelled X.

Given that the wave speed on the rope is 2 m s^{-1}, draw a displacement-time graph for point X between $t = 0$ seconds and $t = 5$ seconds.

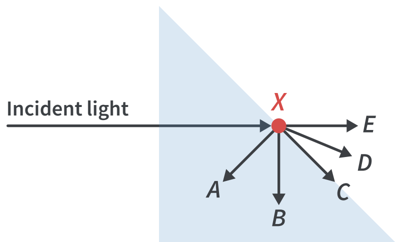


Question 9 (3 MARKS)

How many times can the infrared beam in an underwater communications cable with $n = 1.4$ travel the circumference of the Earth in one second? Take the radius of the Earth to be 6.37×10^6 m, and assume the beam travels a circular path.

Question 10 (2 MARKS)

The refractive index of a prism is 1.35 for red light, 1.38 for yellow light, and 1.45 for blue light. When yellow light is shone into the prism as shown, it is incident on the opposite surface (at point X) at the critical angle.



a Identify which path(s) (A, B, C, D, or E) red light would take if it had the same incident path. (1 MARK)

b Identify which path(s) (A, B, C, D, or E) blue light would take if it had the same incident path. (1 MARK)

Question 11 (2 MARKS)

Three optical fibres are available for purchase from Bunnings. Using calculations, determine which fibre should be used by a cable installer who requires the critical angle within the fibre to be smaller than 67.0°?

Fibre type	n_{core}	$n_{cladding}$
OF-ONION	1.43	1.35
OF-SAUCE	1.43	1.33
OF-SNAGZ	1.43	1.29

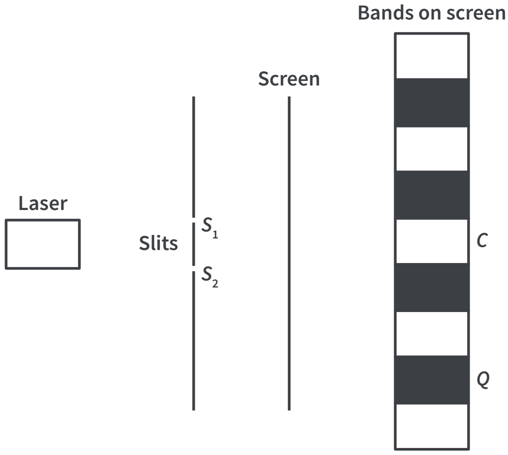
Question 12 (4 MARKS)

Xi, Kim and Donald are carrying out a double-slit experiment with a laser of frequency 5.0×10^{14} Hz. The arrangement of their apparatus is shown. The point *C* is the central bright band of the interference pattern and point *Q* represents the second dark band from *C*.

A Calculate how much larger the distance from S_1 to *Q* is than the distance from S_2 to *Q*. (2 MARKS)

B Xi, Kim and Donald repeat the experiment using a different laser and find that the point *Q* is now the second bright band from *C*. Calculate the wavelength of the new laser. Show your working. (2 MARKS)

Adapted from 2014 VCAA Exam Section A Q19

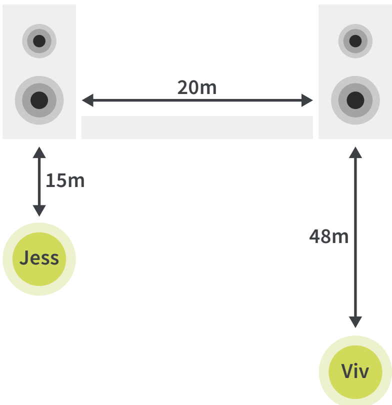


Question 13 (3 MARKS)

Mollie and DeAndre are playing with a 0.50 m string with one fixed end and one free end. They produce a travelling wave in the string with a wavelength of 8.0 cm and a period of 0.020 s. After this, DeAndre attempts to create a standing wave with a frequency of 20 Hz on the same string. Use calculations to identify whether DeAndre will be able to produce this standing wave in the string.

Question 14 (5 MARKS)

Jess and Viv attend a music festival. There are coherent speakers at each end of the 20 m stage. Jess is standing directly in front of the left speaker, 15 m away. Viv is standing directly in front of the right speaker, 48 m away. The note from a bass guitar has a frequency of 85 Hz and the speed of sound is 340 m s^{-1}. Use supporting calculations to describe the intensity of sound received by each of the festival goers. Ignore the effects of any other obstacles at the festival.



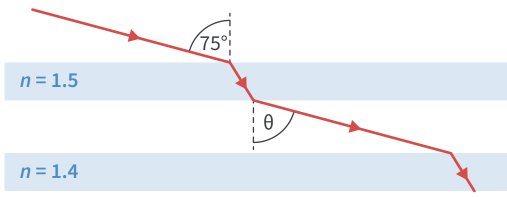
Question 15 (5 MARKS)

A light ray is passing across a double glazed window. All four surfaces of the two layers of glass are parallel. The surrounding medium is air with $n = 1.00$. The light ray hits the top pane at 75° to the normal.

a Calculate the angle of refraction when the ray enters the top layer of glass. (2 MARKS)

b Calculate the angle of refraction when the ray exits the top layer of glass. (1 MARK)

c At what angle does the ray exit the bottom layer of glass? Justify your answer. (2 MARKS)



Question 16 (3 MARKS)

Ms Smyth is a Biology teacher who is covering a VCE Physics class. She tells the class that 'Young's double-slit experiment provides evidence for the wave model of light rather than the particle model of light'. Evaluate Ms Smyth's statement.

Adapted from 2013 VCAA Exam Section A Q22d

Question 17 (3 MARKS)

Two speakers are set up directly facing each other. They output coherent sound waves with a frequency of 425 Hz. Leslie stands in the centre between the two speakers, then walks toward one speaker until she hears the third loud region from the centre. How far has Leslie walked? Take the speed of sound to be 340 m s^{-1}.

Adapted from 2018 VCAA Exam Section B Q11b

Question 18 (3 MARKS)

A length of string has a series of knots on it which are used to identify particular points on the string. Consider two options:

- The string forms a travelling wave with an amplitude of 2.0 cm and a wavelength of 10 cm.
- The string forms a standing wave with an amplitude of 2.0 cm and a wavelength of 10 cm.

Evaluate the statement that 'the motion of each knot does not depend on whether a standing wave or travelling wave exists on the string'.

Question 19 (6 MARKS)

A double-slit experiment is carried out with an apparatus that has two slits separated by 2.00×10^{-5} m.

a Describe, with a reason, the intensity of light at the centre of the interference pattern on the screen. (2 MARKS)

b The laser is replaced with one that has a lower wavelength. The third bright band from the centre of the interference pattern would

A move further away from the centre of the pattern.

B move closer to the centre of the pattern.

C remain in the same position.

D become wider.

(1 MARK)

c The path difference from the slits to the second dark fringe from the centre of the interference pattern is 800 nm. Calculate the path difference, in metres, from the slits to the first bright band from the centre of the pattern. (3 MARKS)

Adapted from 2013 VCAA Exam Section A Q22

UNIT 4

AOS2

How are light and matter similar?

In this area of study students explore the design of major experiments that have led to the development of theories to describe the most fundamental aspects of the physical world – light and matter. When light and matter are probed they appear to have remarkable similarities. Light, which was previously described as an electromagnetic wave, appears to exhibit both wave-like and particle-like properties. Findings that electrons behave in a wave-like manner challenged thinking about the relationship between light and matter, where matter had been modelled previously as being made up of particles.

Outcome 2

On completion of this unit the student should be able to provide evidence for the nature of light and matter, and analyse the data from experiments that supports this evidence.

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UNIT 4 AOS 2, CHAPTER 11

The photoelectric effect – evidence for the particle-like nature of light

11

Key knowledge

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\ max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons
- describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect
- analyse the absorption of photons by atoms, with reference to:
  - the change in energy levels of the atom due to electrons changing state
  - the frequency and wavelength of emitted photons: $E = hf = \frac{hc}{\lambda}$

Image: foxbat/Shutterstock.com

11A EXPERIMENTAL DESIGN OF THE PHOTOELECTRIC EFFECT

Einstein never won a Nobel prize for his work in relativity but he did win one for his understanding of the photoelectric effect experiment. The results of the photoelectric effect experiment support a particle model of light, as we will explore throughout this chapter.

This lesson will look at the independent and dependent variables of the photoelectric effect experiment and introduce the key ideas of the electron-volt, work function, and stopping voltage to be expanded upon in future lessons.

11A Experimental design of the photoelectric effect	11B Changing intensity in the photoelectric effect	11C Changing frequency in the photoelectric effect	11D What the photoelectric effect means

Study design key knowledge dot point

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

Key knowledge units

The electron-volt	4.2.2.7
Understanding the photoelectric effect experiment	4.2.2.1
Work function	4.2.2.6
Dependent and independent variables of the photoelectric effect experiment	4.2.2.2
Stopping voltage as a way to evaluate the maximum kinetic energy of electrons	4.2.2.3

Formulas for this lesson

Previous lessons		New formulas
6A	$W = qV$	No new formulas in this lesson

Definitions for this lesson

electron-volt a measure of energy equal to 1.6×10^{-19} J, derived from the loss or gain of energy by an electron moving across a potential difference of 1 volt

photocurrent the electrical current produced by photoelectrons in the photoelectric effect

photoelectrons electrons emitted in the photoelectric effect

stopping voltage the reverse potential that repels the most energetic electrons from the collector electrode and causes the photocurrent to become zero. It has the same numerical value as the maximum kinetic energy of emitted electrons in electron-volts

work function the minimum energy of light required to release the most loosely bound electron from a metal surface

The electron-volt 4.2.2.7

OVERVIEW

The electron-volt, or eV, is a measure of energy which is useful when describing very small quantities. It will be used alongside the standard measure of energy, the joule, in this chapter to describe the energy of light and photoelectrons.

THEORY DETAILS

From lesson 6A, when a charged particle moves through an electric field it can either lose or gain energy as per the formula $W = qV$. If we consider an electron that moves across a potential difference of 1 volt, given its charge is 1.6×10^{-19} C, we can determine the energy loss or gain by: $W = qV = 1.6 \times 10^{-19} \times 1 = 1.6 \times 10^{-19}$ J

This defines the value of an electron-volt: 1 eV = 1.6×10^{-19} J. The unit eV can be used to describe the energy of anything. It is not confined to electrons.

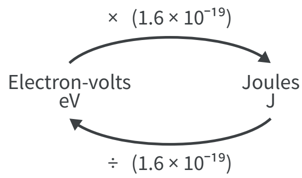


Figure 1 Conversion factor between electron-volts and joules

Understanding the photoelectric effect experiment 4.2.2.1

OVERVIEW

The photoelectric effect demonstrates the effect that light striking a metal surface is able to free electrons from the metal. The electrons released are known as photoelectrons and their movement produces a current known as the photocurrent.

THEORY DETAILS

Metals are made up of positively charged metal cations and negatively charged electrons. These opposite charges exert an electric force on each other that holds the electrons within the metal structure. When light is incident on the metal surface it can cause electrons that are held within the metal to be released, as seen in Figure 2. The frequency (colour) of light can be selected using a filter or a monochromatic light source.

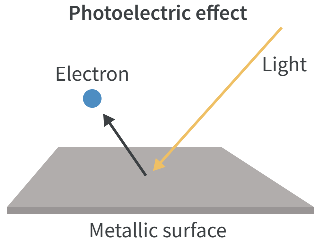


Figure 2 Incident light shone upon a metal surface can result in electrons being released from the surface.

Within the photoelectric effect experiment, this metal surface is referred to as the cathode. Electrons liberated from the metal surface travel to another plate that is known as the collector electrode or anode, and the apparatus of the anode and cathode is known as a photocell. From the collector, these electrons will move through an external circuit that includes an ammeter to measure the photocurrent, and a power supply to produce a variable voltage between the collector electrode and the metal surface.

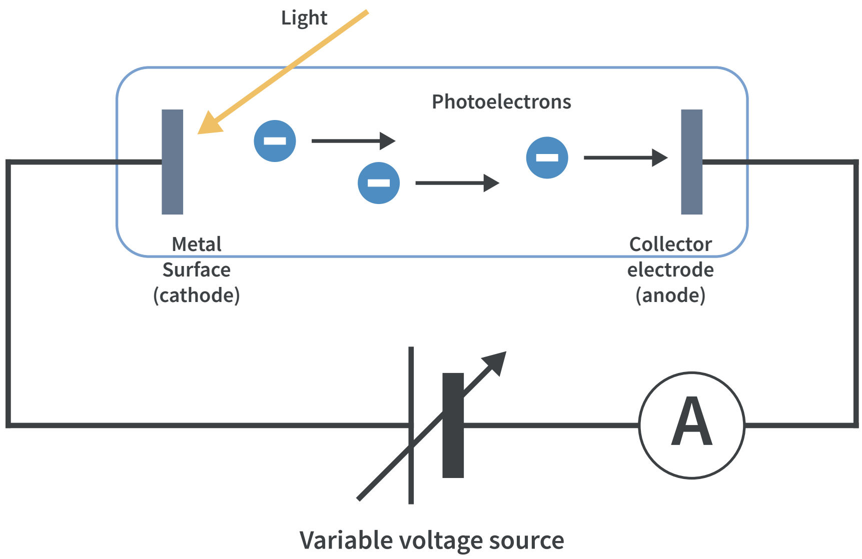


Figure 3 General photoelectric effect experimental setup

Work function 4.2.2.6

OVERVIEW

The work function is a property of a metal that relates to how strongly electrons are held within its structure. This characteristic has an important influence over whether electrons will be liberated from the metal surface (cathode) and, if they are, how much kinetic energy they have.

THEORY DETAILS

Electrons in a metal will be bound with different amounts of energy and therefore require different amounts of energy to be removed. The work function (ϕ or W) is a property that differs between metals. It describes the amount of energy required to release the **most loosely bound electron** from a metal and is most often measured in electron-volts, but it can be measured in joules.

When light interacts with an electron on a metal surface some of the light's energy is used to overcome the work function, and any remaining energy is transferred to the electron as kinetic energy (since energy is conserved). If the light energy absorbed by each electron is less than the work function, electrons cannot be ejected.

This relationship can be expressed as a worded equation:

Electron KE_{max} = *light energy delivered to each electron – work function* (ϕ)

The details of the 'light energy delivered to each electron' will be further explained in lessons 11C and 11D so that the worded equation can be developed into a mathematical equation.

It is important to note that electrons will be ejected with a range of kinetic energies. KE_{max} describes the kinetic energy of the most loosely bound electron which uses the least energy to escape (overcome the work function).

1 **Worked example**

Students conduct a photoelectric experiment in which the sodium metal has a work function of 2.3 eV. Given that each electron absorbs 3.2 eV of energy from the light, calculate the maximum kinetic energy of the photoelectrons produced.

Identify the known values and the relevant relationship.

KE_{max} = *light energy delivered to each electron* − ϕ

light energy delivered to each electron = 3.2 eV

ϕ = 2.3 eV

Substitute values into the equation.

$KE_{max} = 3.2 - 2.3 = 0.9$ eV

Dependent and independent variables of the photoelectric effect experiment 4.2.2.2

OVERVIEW

The photoelectric effect experiment has both independent and dependent variables that are fundamental to the evidence it provides about the nature of light. These ideas will be expanded upon in the following lessons.

THEORY DETAILS

The independent variables of the photoelectric effect experiment are:

- the intensity of light (brightness).
- the frequency of light (colour, when in the visible range).

For an experiment to be valid, measurements must be affected by a single independent variable only: when the intensity of light is changed, the frequency should be kept constant and vice versa. The metal surface, and hence work function, is typically kept constant for a given experiment too.

The dependent variables of the photoelectric effect experiment are:

- the photocurrent.
- the maximum kinetic energy of electrons (KE_{max}).

Photocurrent describes the rate of flow of charge due to the electrons being ejected from the metal surface and reaching the collector anode. It is measured by an ammeter in the external circuit. The maximum kinetic energy of electrons can be predicted using the energy conservation relationship from the previous section, or it can be determined using the stopping voltage which will be discussed in the next section.

Stopping voltage as a way to evaluate the maximum kinetic energy of electrons 4.2.2.3

OVERVIEW

Stopping voltage (V_0 or V_s), alternatively called cut-off potential, is used to measure the maximum kinetic energy of photoelectrons. The magnitude of the stopping voltage, measured in volts, has the same numerical value as the KE_{max} of the electrons when measured in electron-volts.

THEORY DETAILS

The variable voltage source can be used to make the collector anode negatively charged and the metal surface positively charged. This is known as a **reverse potential**. The negatively charged electron is repelled by the negative collector anode and attracted to the positive metal cathode from which it was ejected.

When the reverse potential is increased to the point where even the most energetic electrons do not reach the anode, the current will be zero. At this point the reverse potential is the stopping voltage. The magnitude of the stopping voltage, measured in volts, has the same numerical value as the KE_{max} of the electrons when measured in electron-volts. For example if the **stopping voltage** is 1.7 V then the maximum kinetic energy of electrons is 1.7 eV.

To better understand the idea of determining kinetic energy by measuring another variable, consider the analogy of rolling a ball up a hill. When the ball reaches the top of the hill it will have less kinetic energy than when it started. We can increase the height of the hill until the ball no longer reaches the top. This is similar to increasing the reverse potential until the current becomes zero. If we know the mass of the ball (which is like knowing the charge of the electron) we could determine the initial kinetic energy of the ball by measuring the height of the hill required to stop the ball reaching the top. Similarly, the size of the V_0 tells us the KE_{max} of the electrons.

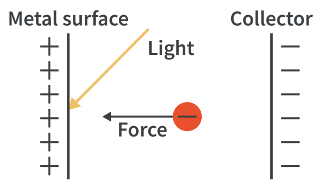


Figure 4 A reverse potential applies a force on photoelectrons directed back towards the metal surface cathode.

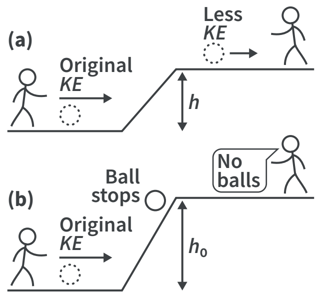


Figure 5 Reverse potential is like a hill up which a ball must roll. **(a)** If the ball reaches the top it will have less kinetic energy than at the bottom. **(b)** Stopping voltage is equivalent to the height of a hill which stops a ball reaching the top (h_0).

2 Worked example

Bill and Bob wish to find the work function of a metal. It is known that light incident on the metal surface transfers 4.7 eV to each electron and it is found that when a reverse potential of 1.2 V is applied, the current reaches to zero. What is the work function of the metal?

Identify that the reverse potential at which current drops to zero is the stopping voltage, which has the same numerical value as the maximum kinetic energy of the electrons in eV.

KE_{max} = 1.2 eV

light energy delivered to each electron = 4.7 eV

KE_{max} = *light energy delivered to each electron* − ϕ

Substitute values into the equation.

$1.2 = 4.7 - \phi$

ϕ = 3.5 eV

Theory summary

- An electron-volt is a measure of energy that is equivalent to 1.6×10^{-19} J.
- The photoelectric effect describes how light is able to free electrons, called photoelectrons, from a metal surface to produce a photocurrent.
- The independent variables of the photoelectric effect experiment are:
  - the intensity of light.
  - the frequency of light.
- The dependent variables of the photoelectric effect experiment are:
  - the photocurrent
  - the maximum kinetic energy of electrons (KE_{max}) measured in electron-volts or joules, which can be determined by measuring the stopping voltage in volts.
- The work function is specific to each metal and is the amount of energy required to free the most loosely bound electron.
- The maximum kinetic energy of electrons is given by: KE_{max} = *light energy delivered to each electron* − ϕ.

11A Questions

THEORY REVIEW QUESTIONS

Question 1

An electron moves against a potential difference of 3 V. The energy loss in both joules and electron-volts respectively is

A 3 J and 4.8×10^{19} eV.

B 3 J and 1.875×10^{-19} eV.

C 4.8×10^{-19} J and 3 eV.

D 1.875×10^{19} J and 3 eV.

Question 2

Complete the table using the appropriate variables below for the photoelectric experiment using a sodium metal surface. Not all options need to be used.

V1: kinetic energy of electrons

V2: frequency of light

V3: photocurrent

V4: work function of metal surface

V5: frequency of electrons

V6: brightness/intensity of light

V7: brightness of electrons

Independent variable(s)	Dependent variable(s)	Controlled variable(s)

Question 3

Stopping voltage measured in volts has the same numerical value as

A KE_{max} in eV.

B work function in eV.

C KE_{max} in V.

D light energy in eV.

Question 4

The work function is best described as

A the maximum energy of incident light required to liberate electrons from a collector electrode.

B a property of metals due to the interaction of negative cations and positive electrons.

C the energy of incident light in the photoelectric experiment.

D the minimum energy of incident light required to liberate electrons from a specific metal surface.

Question 5

The maximum kinetic energy of a liberated electron is equal to the difference between

A the stopping voltage and the work function of the metal.

B the energy of incident light absorbed by an electron and the stopping voltage.

C the kinetic energy of electrons and the energy of incident light.

D the energy of incident light absorbed by an electron and the work function of the metal.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

The surface of a metal has a work function of 3.2 eV.

What is the minimum energy that light must transfer to an electron to release a photoelectron in joules?

Adapted from 2018 VCAA NHT Exam Section A Q17

Question 7

A specific metal used in a photoelectric experiment has a work function of 2.3 eV and ejects electrons at a maximum energy of 0.2 eV from the cathode. What is the cut-off potential required so that no photoelectrons reach the anode?

A 0.2 V

B 2.1 V

C 2.3 V

D 2.5 V

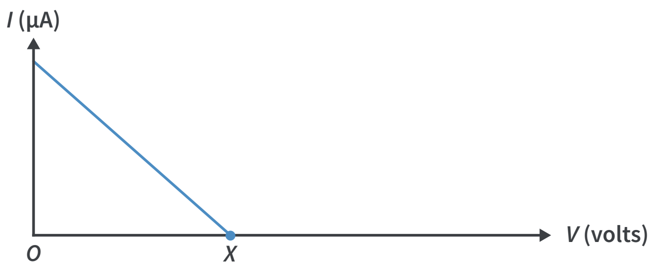
Question 8 (2 MARKS)

An electron has a mass of 9.1×10^{-31} kg and is shot out of an electron gun at a speed of 2.2×10^{6} m s^{-1}.

Measured in electron-volts, what is the kinetic energy of the electron?

Question 9 (5 MARKS)

The graph depicts the results obtained when comparing the magnitude of the reverse potential measured in volts and the photocurrent measured in μA in a standard photoelectric experiment.



a Explain why the current drops to zero at point *X*, and how kinetic energy of electrons is determined in the photoelectric experiment. (3 MARKS)

b Given the value of *X* is 1.1, determine the maximum kinetic energy of the electrons in both electron-volts and joules. (2 MARKS)

Adapted from 2011 VCAA Exam 2 Section A AoS 2 Q5

Question 10 (2 MARKS)

During an investigation into the photoelectric effect, a scientist uses light which can transfer energy of 3.70 eV to an electron in the attempt to release electrons from a metal of work function $\phi = 2.90$ eV. The scientist also decides to use joules in her final answer to impress her non-science friends with scientific notation.

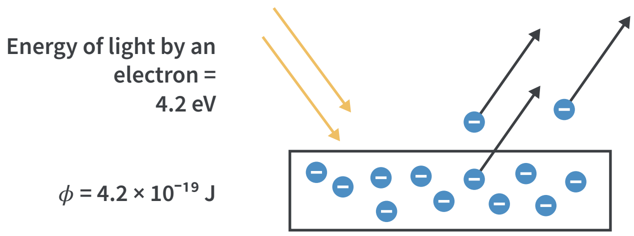
What value would she obtain for the maximum kinetic energy of the photoelectrons?

Question 11 (2 MARKS)

A specific metal has a work function of 2.8 eV. Describe the kinetic energies of the ejected electrons when each electron absorbs 2.9 eV from light incident on the metal surface. Explain your answer.

Question 12 (2 MARKS)

From the diagram find the maximum kinetic energy of the ejected electrons in electron-volts.



Question 13 (3 MARKS)

Bill sets up an apparatus to study the photoelectric effect in which the light used can transfer an energy of 2.8 eV to individual electrons in the metal surface. Bill uses a variable power supply to create a reverse potential between the cathode and anode. He finds that the lowest value of reverse potential for which no current is measured is 0.6 V.

Determine the work function of the metal. Show your working.

Adapted from 2017 VCAA NHT Exam Section B Q18

Question 14 (3 MARKS)

Tony Stark decides to take time out of his busy day to investigate the photoelectric effect with zinc metal. Using his hand lasers, he fires monochromatic light onto a zinc metal surface. He applies a reverse potential which, when it reaches 6.67 V, stops all photoelectrons from reaching the collector. The work function of the zinc metal is 6.93×10^{-19} J.

What is the energy absorbed by each electron due to the incident light in joules? Show your working.

Previous lessons

Question 15 (2 MARKS)

At a point on the surface of the planet Mars, which is R metres from the centre, the value of the gravitational field strength is 3.71 N kg^{-1}. Calculate the magnitude of the gravitational field strength at a distance 3R above the surface of Mars.

Adapted from 2018 VCAA Exam Section A Q7

Question 16 (2 MARKS)

Two bodies of an equal mass of 8.50×10^{22} kg are attracted by a force of 3.40×10^{17} N.

Find the distance between the centres of the two masses.

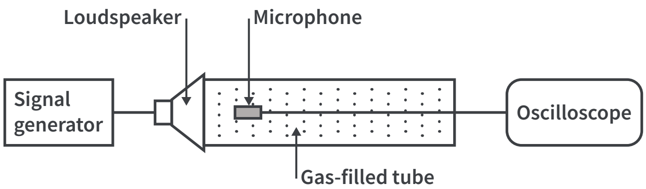
Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 17 (1 MARK)

A physics student sets up a speaker which produces 180 Hz sound waves. Given the speed of sound is 340 m s^{-1}, find the wavelength of the sound waves.

Question 18 (2 MARKS)

Students utilise a tube filled with hydrogen to investigate the speed of sound through a gas. They measure the distance between the microphone and the loudspeaker to be 0.25 m and the time taken for sound to travel between them to be 0.20 ms. Knowing that the wavelength of the sound used is 9.0 m, calculate the frequency of sound used.



Key science skills

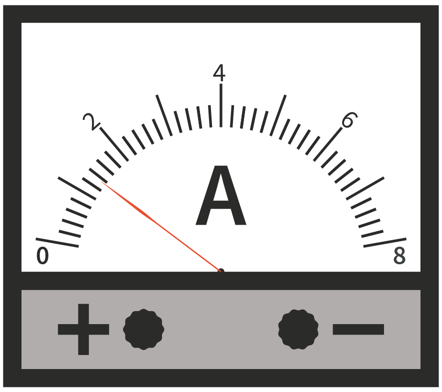
Question 19 (2 MARKS)

Investigations into the photoelectric effect have multiple independent and dependent variables. Outline a key controlled variable of the photoelectric experiment and explain why it is necessary to keep it controlled.

Adapted from 2017 VCAA Sample Exam Section B Q17e

Question 20 (1 MARK)

This ammeter is used to measure the photocurrent during a photoelectric effect experiment. What is the uncertainty in its measurements?



Adapted from 2018 VCAA Exam Section A Q19

11B CHANGING INTENSITY IN THE PHOTOELECTRIC EFFECT

This lesson explores the impact of changing the intensity of incident light on the results of the photoelectric effect. The interpretation of these results as evidence for a particle model of light will be explored in lesson 11D.

11A Experimental design of the photoelectric effect	11B Changing intensity in the photoelectric effect	11C Changing frequency in the photoelectric effect	11D What the photoelectric effect means

Study design key knowledge dot point

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

Key knowledge units

Photoelectric effect graphs	4.2.2.5
Effect of changing the intensity of light	4.2.2.9.1

No previous or new formulas for this lesson

Photoelectric effect graphs 4.2.2.5

OVERVIEW

There are two kinds of graphs commonly used to analyse the photoelectric effect: photocurrent-electrode potential graphs and kinetic energy-frequency graphs (explored further in lesson 11C).

THEORY DETAILS

Photocurrent-electrode potential graphs

These graphs show the photocurrent for all values of potential or reverse potential caused by incident light of a fixed frequency and intensity. If either frequency or intensity change, the graph will change. There are two key features that we need to interpret from photocurrent-electrode potential graphs.

Table 1 Key features of photocurrent-potential graphs

Photocurrent-potential graph feature	What the feature represents
Horizontal axis intercept	Negative value of stopping voltage ($-V_s$)
Maximum vertical axis value	Maximum photocurrent

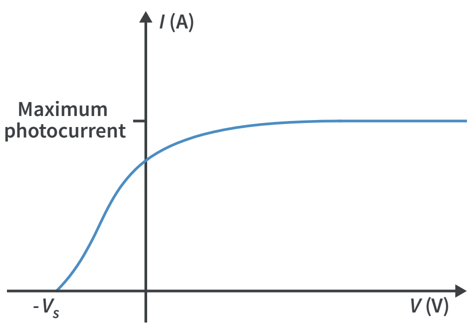


Figure 1 Photocurrent-potential graph for the photoelectric effect. The horizontal axis intercept is the negative value of the stopping voltage.

When the applied voltage is positive, electrons emitted from the metal surface are attracted to the anode (or collector). When the applied voltage is negative (reverse potential), emitted electrons are repelled from the anode so that fewer photoelectrons are able to reach it. At a certain reverse potential called the stopping voltage, no photoelectrons will be able to reach the collector. This occurs at the horizontal axis intercept on a photocurrent-potential graph.

The photocurrent is determined by how many photoelectrons travel from the cathode to the anode every second. Only a small positive voltage is needed to collect all emitted photoelectrons at the collector.

A more positive voltage does not liberate more photoelectrons. This is represented by the photocurrent flattening out to a maximum current after a small positive potential.

Kinetic energy-frequency graphs

The results of the photoelectric effect generate a kinetic energy-frequency graph with a positively sloped linear trendline. The intercept on the horizontal axis is the 'threshold frequency'. The features of this graph will be explored in more detail in lesson 11C.

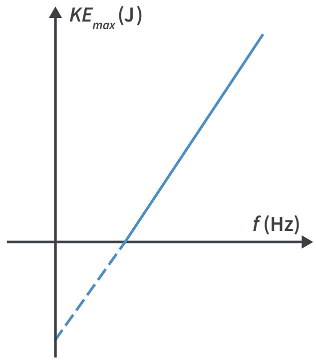


Figure 2 Kinetic energy-frequency graph for the photoelectric effect

Effect of changing the intensity of light 4.2.2.9.1

OVERVIEW

Changing the intensity of the incident light in the photoelectric effect experiment affects the maximum photocurrent but does not affect the kinetic energy of the emitted photoelectrons.

THEORY DETAILS

When the intensity of light incident on the metal surface is increased, more electrons are emitted every second. As such, **an increase in the intensity of the light causes an increase in the maximum current**. Similarly, a decrease in the intensity of light causes a decrease in the maximum current.

Changing the intensity of light does not change the stopping voltage and therefore it does not change the kinetic energy of photoelectrons (assuming frequency is constant).

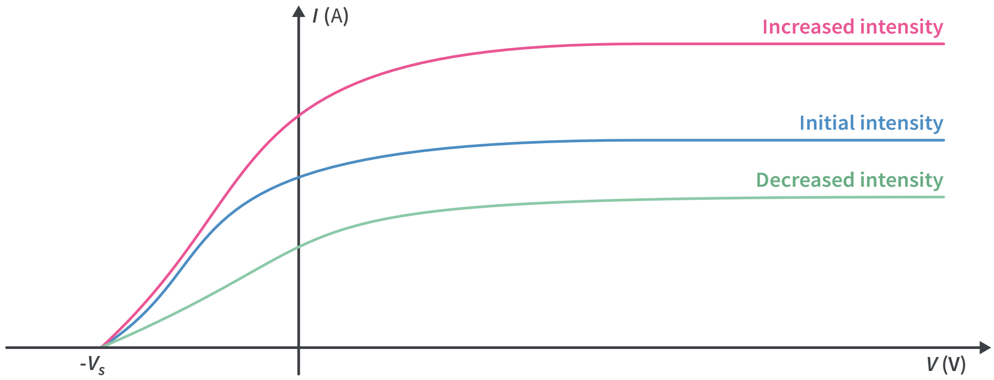


Figure 3 The maximum photocurrent is different for different intensities of light, but the stopping voltage is the same for all intensities of light that have the same frequency.

Since the intensity has no impact on the kinetic energy of the emitted electrons, a kinetic energy-frequency graph does not change if the intensity is changed. The work function (metal surface) is the only variable that can change the position of a kinetic energy-frequency graph.

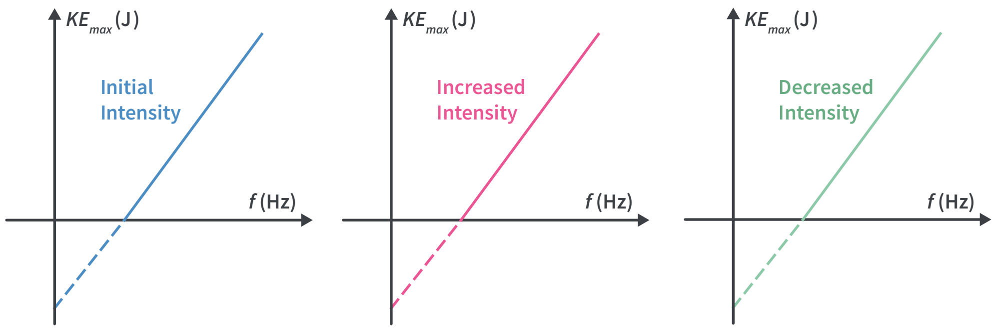


Figure 4 Increasing or decreasing the intensity of light has no impact on kinetic-energy frequency graphs. The increased or decreased intensity graph is exactly the same as the initial graph.

Theory summary

- The data from the photoelectric effect can be displayed on photocurrent-potential graphs and kinetic energy-frequency graphs.
- Photocurrent-potential graphs display two important features:
  - maximum photocurrent
  - stopping voltage which is shown as the negative of the horizontal axis intercept
- Increasing the incident light intensity results in an increase in maximum photocurrent.
- Changing the intensity does not change the stopping voltage (the kinetic energy of the photoelectrons is unchanged).

KEEN TO INVESTIGATE?

PhET 'Photoelectric effect' simulation
https://phet.colorado.edu/en/simulation/photoelectric

The Physics Aviary 'Photoelectric Effect Lab'
https://thephysicsaviary.com/Physics/Programs/Labs/PhotoelectricEffect/index.html

11B Questions

THEORY REVIEW QUESTIONS

Question 1

Which important quantity can be determined from the horizontal axis intercept of the photocurrent-potential graph?

A The maximum current

B The threshold frequency

C The minimum kinetic energy

D The stopping voltage

Question 2

What is the best explanation for why the photocurrent plateaus as voltage increases in the photoelectric effect?

A Only a small voltage is needed to collect all emitted photoelectrons.

B No electrons are able to reach the anode.

C The frequency is above the threshold frequency.

D Electrons are emitted from the cathode to the anode.

Question 3

What feature of the current-voltage graph indicates that the kinetic energy of the photoelectrons does not change with doubling intensity?

A The current doubling

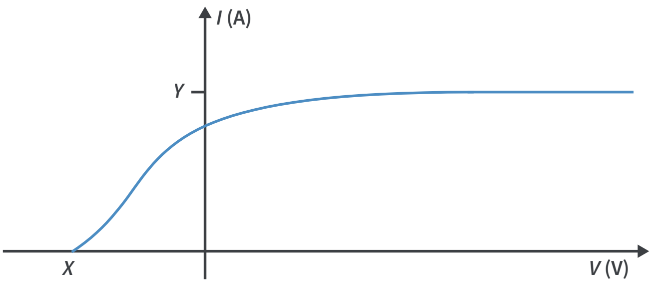
B The current not changing

C The value of the stopping voltage doubling

D The value of the stopping voltage staying the same

Question 4

Consider the photocurrent-potential graph shown. *X* represents the value at the horizontal axis intercept and *Y* represents the maximum value on the vertical axis.



Choose the option which best describes how the values of *X* and *Y* would be affected if the intensity of incident light was reduced while the frequency was held constant.

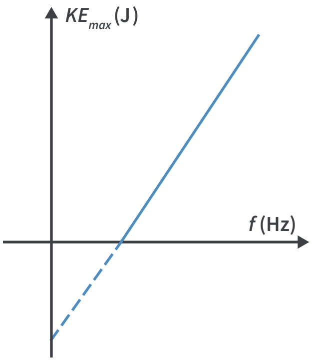
	Change to *X*	Change to *Y*
A	No change	Decrease
B	Decrease in magnitude	Decrease
C	Decrease in value	No change
D	No change	No change

EXAM-STYLE QUESTIONS

This lesson

Question 5 (2 MARKS)

Colin is performing a photoelectric effect experiment, analysing how changing the frequency of light impacts the maximum kinetic energy of the emitted electrons.
He produces the graph shown. He then doubles the intensity of the light and repeats the experiment. Copy the original graph (for comparison) and draw a graph of the results of the repeated experiment. Justify the similarities and/or differences between the graphs.

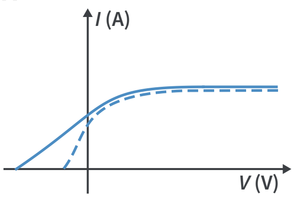


Adapted from 2015 VCAA Exam Section A Q18c

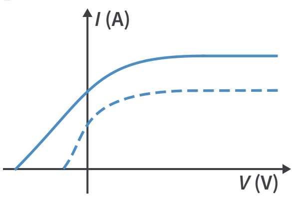
Question 6 (2 MARKS)

a Katie is measuring the current produced when she varies the applied voltage in the photoelectric effect experiment, plotting the results as a dashed line.
She then doubles the intensity of the light (keeping the frequency of light constant) and plots the results as a continuous line. Identify which graph below best illustrates the results of the second experiment. (1 MARK)

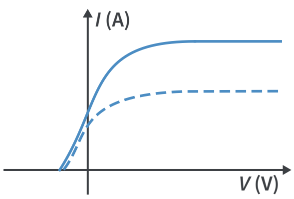
A



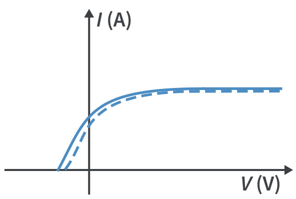
B



C

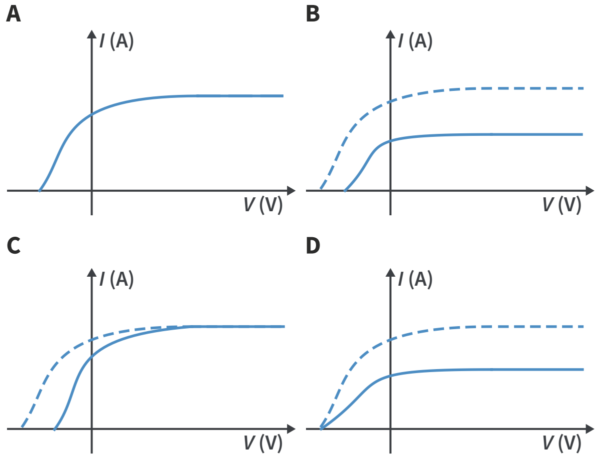


D



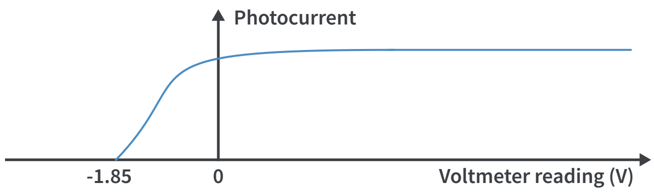
Adapted from 2017 VCAA NHT Exam Section A Question 18e

b Bradley then repeats the photoelectric effect experiment initially performed by Katie but he decides to use light with half of the original intensity. Katie's original results are shown with a dashed line. Bradley's results are indicated by a continuous line. Identify which graph below best illustrates the results of the second experiment. (1 MARK)



Question 7 (1 MARK)

Using the graph, calculate the maximum kinetic energy in joules of the photoelectrons in this photoelectric effect experiment.

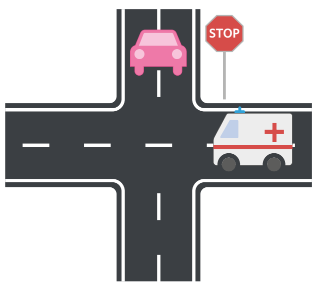


2013 VCAA Exam Section A Question 21a

Previous lessons

Question 8 (2 MARKS)

Gen is stopped at a stop sign while an ambulance drives through the intersection with its siren blaring. Describe how the sound Gen hears will vary as the ambulance approaches, is directly in front of her, and then continues to drive away and identify the principle responsible for what she observes.



Question 9 (3 MARKS)

The International Space Station (ISS) has a mass of 4.17×10^5 kg. Take the mass of the Earth to be 5.98×10^{24} kg, the radius of the Earth to be 6.37×10^6 m and $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

a Calculate the magnitude of the gravitational field strength 400 km above the Earth's surface. (2 MARKS)

b Hence calculate the magnitude of the gravitational force experienced by the ISS as it orbits at this height. (1 MARK)

Key science skills

Question 10 (5 MARKS)

In a photoelectric effect experiment, we usually consider light intensity and frequency to be the independent variables and consider photocurrent and electron kinetic energy to be the dependent variables. However, intensity and frequency are both constant when generating a single photocurrent-potential graph.

a Explain why voltage is an independent variable and the photocurrent is a dependent variable when generating a single current-voltage graph. (2 MARKS)

b When performing the photoelectric effect to generate a current-voltage graph, what kind of variable is the intensity of the incident light? (1 MARK)

c If the aim of an experiment about the photoelectric effect is to understand the impact of changing intensity of incident light on the maximum photocurrent, what kind of variable does intensity become? Justify your answer. (2 MARKS)

11C CHANGING FREQUENCY IN THE PHOTOELECTRIC EFFECT

Does light behave as a wave or a particle? This lesson will highlight a key piece of evidence to help answer this question by analysing the impacts of changing frequency in the photoelectric effect. The implications of the results will be examined in the next lesson.

11A Experimental design of the photoelectric effect	11B Changing intensity in the photoelectric effect	11C Changing frequency in the photoelectric effect	11D What the photoelectric effect means

Study design key knowledge dot point

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

Key knowledge units

Effect of changing the frequency of light	4.2.2.9.2
The relationship between electron kinetic energy and frequency of light	4.2.2.8

Formulas for this lesson

Previous lessons	New formulas
No previous formulas in this lesson	* $KE_{max} = hf - \phi$
	$\phi = hf_0$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

Planck's constant a constant equal to 6.63×10^{-34} J s or 4.14×10^{-15} eV s

threshold frequency the minimum frequency of light at which electrons are ejected from a metal surface in the photoelectric effect

Effect of changing the frequency of light 4.2.2.9.2

OVERVIEW

Changing the frequency of the incident light in the photoelectric effect experiment affects the kinetic energy of emitted electrons but does not affect the maximum current.

THEORY DETAILS

When the **frequency of incident light is increased, the kinetic energy of released photoelectrons increases** which suggests each electron absorbs more energy. However, **the number of electrons released does not change**, maintaining a constant photocurrent. This is conditional on the incident light being above the threshold frequency, which will be discussed later in the lesson.

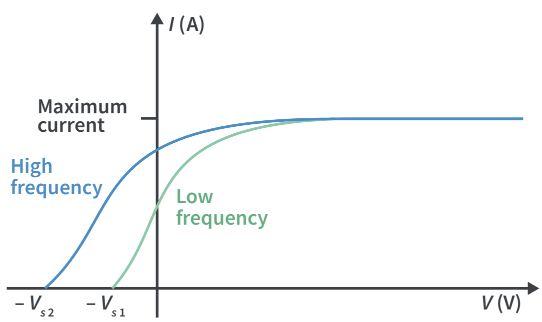


Figure 1 For higher frequencies there will be a larger stopping voltage due to increased KE_{max}. Maximum current is not affected by the frequency of light.

The relationship between electron kinetic energy and frequency of light 4.2.2.8

OVERVIEW

The relationship between electron kinetic energy and frequency of light can be seen in the equation $KE_{max} = hf - \phi$. This resembles a general linear equation, $y = mx + c$, and can be used to explain elements of the kinetic energy-frequency graph.

THEORY DETAILS

A kinetic energy-frequency graph shows the value of the maximum kinetic energy of photoelectrons (or stopping voltage) for a range of frequencies of light when incident on a specific metal surface. It indicates a positively sloped linear relationship between the kinetic energy of photoelectrons (or stopping voltage) and frequency. There are three key features that we need to interpret from these graphs.

Table 1 Key features of kinetic-energy frequency graphs.

Kinetic energy-frequency graph feature	What the feature represents
Horizontal axis intercept	Threshold frequency (f_0)
Vertical axis intercept	Negative value of work function ($-\phi$)
Gradient	Planck's constant (h)

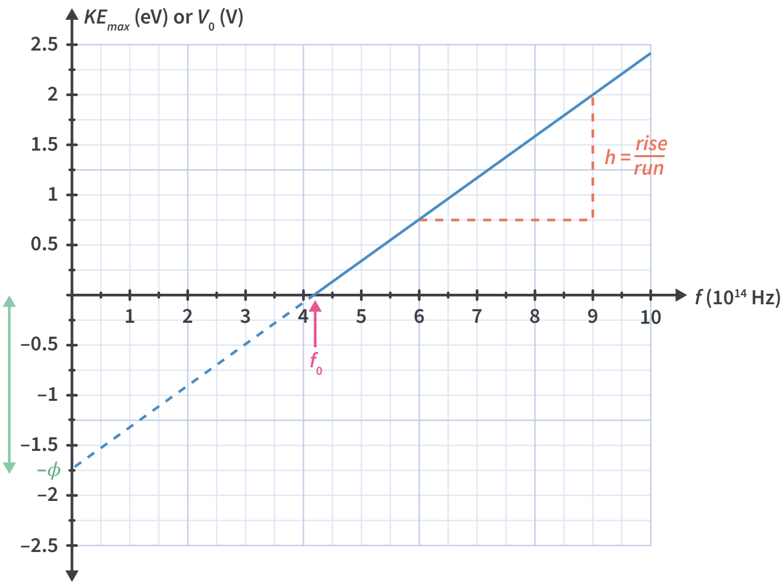


Figure 2 Kinetic energy-frequency graphs are linear relationships with a gradient equal to Planck's constant h. It is also common to use joules for the kinetic energy on the vertical axis. The horizontal intercept is the threshold frequency and the vertical intercept is the negative value of the work function.

USEFUL TIP

It is common for the exam to ask students to find Planck's constant from a graph or set of data. In this case find the gradient of the line of best fit. Do not quote values of Planck's constant from the formula sheet.

1 Worked example

From Figure 2, determine

a **work function.**

b **threshold frequency.**

c **Planck's constant.**

a Work function is the negative of the vertical axis intercept: $\phi = 1.75$ eV

b Threshold frequency is the horizontal axis intercept: $f_0 = 4.25 \times 10^{14}$ Hz

c For Planck's constant use two points on line to calculate gradient:

$$h = \frac{rise}{run} = \frac{2.0 - 0.75}{9.0 \times 10^{14} - 6.0 \times 10^{14}} = 4.2 \times 10^{-15} \text{ eV s}$$

The kinetic energy-frequency graph shows an independent variable (frequency) on the horizontal axis and a dependent variable (kinetic energy or stopping voltage) on the vertical axis. That is, a single graph shows the KE_{max} of photoelectrons **for a range of frequencies**. The specific metal surface (and its work function) is the only variable that can change a kinetic energy-frequency graph. The graph is not affected by intensity. This contrasts the photocurrent-potential graphs where each graph represents only a single frequency and intensity.

The negative portion of the kinetic energy-frequency graph is dashed as it is not physically valid to have negative kinetic energy. However, it is often drawn as an extension of the positive portion to show the work function.

This linear relationship can be understood by comparing the general linear equation $y = mx + c$ with the equation from lesson 11A: $KE_{max} = \textit{light energy} - \phi$. We can conclude that

- light energy must be proportional to its frequency: $\textit{light energy} = hf$ where h is the gradient of the graph.
  - This gradient is known as Planck's constant (h). This is comparable to the gradient m in the general equation $y = mx + c$.
- work function must be the negative value of the vertical intercept.
  - This is comparable to the c in the general equation $y = mx + c$. The vertical intercept on a kinetic energy-frequency graph has a negative value but work function is a positive number.

We can substitute $\textit{light energy} = hf$ into our KE_{max} equation from lesson 11A, where h is a constant.

$$KE_{max} = hf - \phi$$

KE_{max} = maximum kinetic energy of electrons (eV or J), h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s), f = frequency (Hz), ϕ = work function (eV or J)

Using Planck's constant

Planck's constant has two different values and units that **cannot** be used interchangeably.

- 6.63×10^{-34} J s
  - Use this value when all values in an equation are measured in SI units (including joules).
  - This will be the value of the gradient of a kinetic energy-frequency graph when the maximum kinetic energy values are measured in joules.
- 4.14×10^{-15} eV s
  - Use this value when working in electron-volts and when the desired answer is in electron-volts.
  - This will be the value of the gradient of a stopping voltage-frequency graph or a kinetic energy-frequency graph when the maximum kinetic energy values are measured in electron-volts.

2 Worked example

During a photoelectric experiment, light of frequency 8.5×10^{14} Hz is incident on a metal surface which has a work function of 3.0 eV or 4.8×10^{-19} J. Find the maximum kinetic energy of electrons in:

a **electron-volts.**

b **joules.**

a $KE_{max} = hf - \phi = 4.14 \times 10^{-15} \times 8.5 \times 10^{14} - 3.0$

$KE_{max} = 0.52$ eV

b $KE_{max} = hf - \phi = 6.63 \times 10^{-34} \times 8.5 \times 10^{14} - 4.8 \times 10^{-19}$

$KE_{max} = 8.4 \times 10^{-20}$ J

Threshold frequency

The threshold frequency is a property that differs between metals and indicates the minimum frequency of light required to release electrons from a metal cathode. As the frequency of light is related to energy, threshold frequency can be linked to an explicit energy value: the work function. That is, threshold frequency is the minimum frequency of light required for electrons to overcome the work function. If incident frequency is below the threshold frequency, the photocurrent will be zero (regardless of intensity).

At the point where the kinetic-energy frequency graph intersects the horizontal axis, all the light energy absorbed by electrons has been used to escape from the metal surface. This intersection represents the threshold frequency.

$$\phi = hf_0$$

ϕ = work function (eV or J), h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s), f_0 = threshold frequency (Hz)

Knowing this, we can modify our equation for KE_{max}:

$$KE_{max} = hf - hf_0 = h(f - f_0)$$

3 Worked example

The threshold frequency of sodium is 4.40×10^{14} Hz. Determine the work function of sodium in electron-volts.

Choose $h = 4.14 \times 10^{-15}$ eV s to obtain a result in electron-volts.

$\phi = hf_0 = 4.14 \times 10^{-15} \times 4.40 \times 10^{14} = 1.82$ eV

Different metals have different work functions and will translate the kinetic energy-frequency graph in the vertical direction. This is equivalent to changing the value of c in the general equation $y = mx + c$. This means different metals have different threshold frequencies but their kinetic energy-frequency graphs will remain parallel with a gradient equal to Planck's constant.

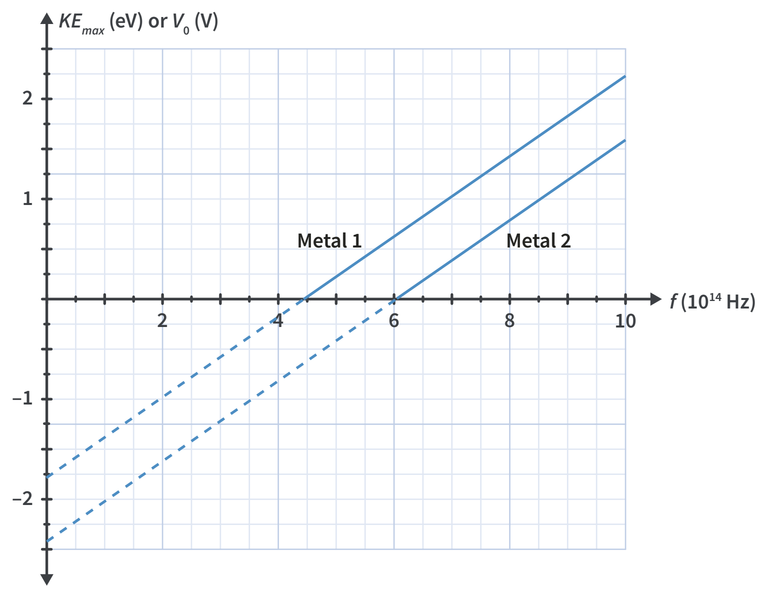


Figure 3 Kinetic energy-frequency graphs for two different metals

Theory summary

- Changing the frequency of light incident on a metal surface will directly alter the kinetic energy of photoelectrons and hence their stopping voltage, but have no impact on the number of electrons released and therefore the current produced.
- Kinetic energy-frequency graphs show the KE_{max} of photoelectrons for all frequencies of light incident on a specific metal surface.
  - The horizontal axis intercept represents the threshold frequency, f_0.
  - The vertical axis intercept represents the negative work function, $-\phi$.
  - The gradient represents Planck's constant, h.
- The graph can be described by the equation $KE_{max} = hf - \phi$, where h is Planck's constant equal to 6.63×10^{-34} J s or 4.14×10^{-15} eV s.
- The threshold frequency f_0 is the minimum frequency of light required to release photoelectrons from a metal surface. If $f < f_0$, there will be no photocurrent.
- The work function is linked to the threshold frequency by the equation $\phi = hf_0$, forming the equation $KE_{max} = hf - hf_0 = h(f - f_0)$

KEEN TO INVESTIGATE?

PhET 'Photoelectric effect' simulation
https://phet.colorado.edu/en/simulation/photoelectric

The Physics Aviary 'Photoelectric Effect Lab'
https://www.thephysicsaviary.com/Physics/Programs/Labs/PhotoelectricEffect/index.html

11C Questions

THEORY REVIEW QUESTIONS

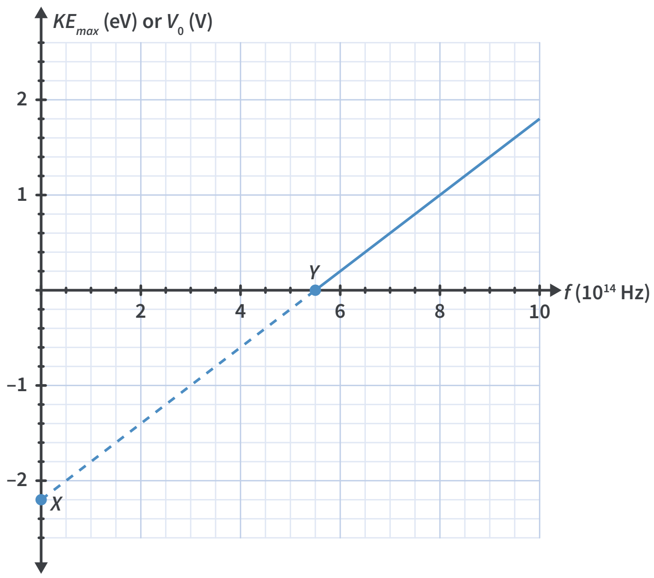
Question 1

Which combination best describes the effect of increasing frequency in the photoelectric effect? Assume the original frequency is already greater than the threshold frequency.

	Photocurrent	Kinetic energy of electrons
A	Decreases	Increases
B	Does not change	Increases
C	Does not change	Decreases
D	Increases	Does not change

Use the following information to answer Questions 2 and 3.

The graph shows the kinetic energy of electrons and the frequency of light in a photoelectric experiment.



Question 2

Which option correctly describes X and Y on the graph?

A X = work function, Y = threshold frequency

B X = Planck's constant, Y = threshold frequency

C X = threshold frequency, Y = work function

D X = negative work function, Y = threshold frequency

Question 3

Which of the following changes would cause the graph to change?

A Decreasing the frequency of incident light

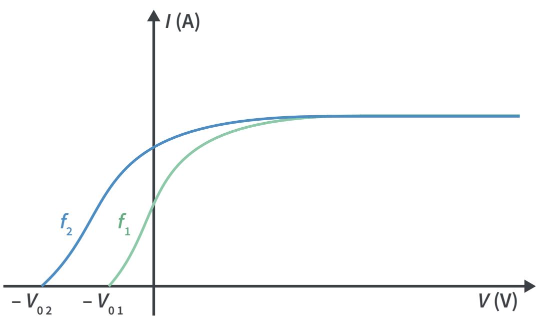
B Increasing the intensity of incident light

C Changing the specific metal used

D All of the above

Question 4

From this current-voltage graph, what can be concluded about the relative size of the frequencies f_1 and f_2?



A $f_2 < f_1$

B $f_2 > f_1$

C $f_2 = f_1$

D There is not enough information to make a conclusion.

Question 5

Threshold frequency is best described as

A the minimum frequency of incident light required to release electrons from a metal surface.

B the energy of incident light required to overcome a reverse potential.

C the frequency corresponding to the maximum kinetic energy of electrons.

D a frequency that is the same for all metals causing photoelectrons to be released.

EXAM-STYLE QUESTIONS

This lesson

Question 6 (1 MARK)

If a metal has a threshold frequency of 3.6×10^{14} Hz, what is the value of the metal's work function in electron volts?

A 1.5 eV

B 0.1 eV

C 2.4×10^{-19} eV

D 1.4 eV

Question 7 (2 MARKS)

Two students, Sam and Isabella, are conducting a photoelectric experiment and have conflicting views as to why they observe no photocurrent despite light being incident on the metal surface. Sam says that if they simply increase the brightness of the light, they will measure a current. Isabella suggests that only by increasing the frequency will they produce a current. Who is correct? Explain your answer.

Adapted from 2018 VCAA Exam Section B Q17ai

Question 8 (4 MARKS)

A metal is illuminated with light that has a frequency of 9.5×10^{14} Hz and is found to eject electrons at an energy of 0.80 eV.

a What is the work function of the metal in electron-volts? (2 MARKS)

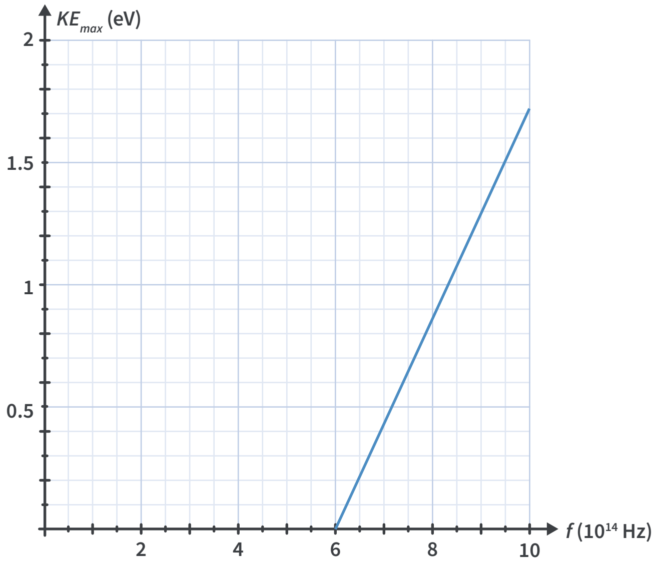
b What is the value of the metal's threshold frequency? (2 MARKS)

Question 9 (2 MARKS)

It turns out that Green Lantern's green lantern has a frequency of 5.5×10^{14} Hz, which corresponds to the threshold frequency of a metal cathode. What frequency of light must be used on this metal for photoelectrons to have a maximum kinetic energy of 2.6×10^{-19} J?

Question 10 (2 MARKS)

The graph shows the maximum kinetic energy vs frequency for a photoelectric experiment. In a subsequent experiment, the scientists decide that they will use a metal with a work function one third larger than the original metal. Copy the graph and use a dotted line to show what the graph will look like with the new metal.



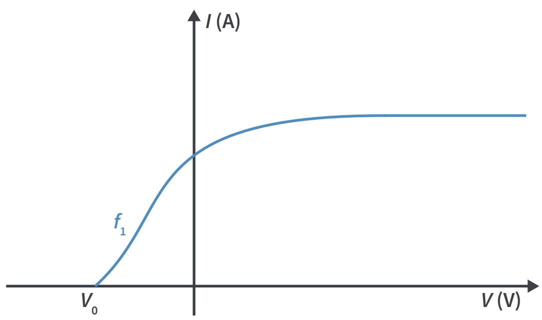
Adapted from 2015 VCAA Exam Section A Q18d

Question 11 (3 MARKS)

Pauline conducts a photoelectric experiment in which the incident light has a frequency of 7.3×10^{14} Hz and the metal cathode has a threshold frequency of 5.8×10^{14} Hz.

a Calculate the stopping voltage. (2 MARKS)

b Pauline then repeats the experiment with a new frequency, f_2, whilst maintaining a constant intensity. This frequency is larger than the previous frequency f_1. The graph shows the current-voltage curve for the original frequency. Copy the graph and sketch the new curve that Pauline would obtain on the with a dotted line. (1 MARK)



Question 12 (6 MARKS)

A scientist is conducting a photoelectric experiment to determine the work function of a newly discovered metal that landed on Earth in an asteroid. To accomplish this, she sets her laser to 375 nm and shines it onto the metal, recording the maximum kinetic energy of released electrons to be 1.25 eV.

a Calculate the work function of the metal in joules. (4 MARKS)

b Calculate the threshold frequency. (2 MARKS)

Previous lessons

Question 13 (5 MARKS)

Steve has one goal in his life: to feel like he is on the Moon. He plans to build a rocket and instead of going to the moon, because that is scary, he will fly into space until the gravitational field strength from Earth is equivalent to that on the surface of the Moon.

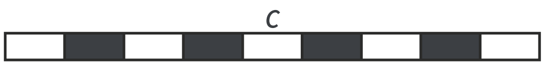
a Knowing that the gravitational acceleration on the Moon is 1.62 m s^{-2}, how far will Steve need to be above the surface of the Earth to achieve this?

Take the radius of the Earth to be 6.37×10^6 m, and its mass to be 5.98×10^{24} kg. (3 MARKS)

b If Steve is orbiting the Earth at the altitude identified in part **a** of this question, will he feel the same as standing on the Moon? Explain your answer. (2 MARKS)

Question 14 (4 MARKS)

Three physics students are conducting a double-slit experiment and decide to use a laser that has a wavelength of 595 nm. The interference pattern they produce is shown. There is a bright band at point *C* in the centre of the pattern.



a Explain why a bright band is seen at the centre of the pattern rather than a dark band. (2 MARKS)

b When measuring the distance between each slit and one of the dark bands to the left of the centre, they find that the difference in the path is 8.925×10^{-7} m. Copy the pattern and mark the relevant band. Justify your answer with a calculation. (2 MARKS)

Adapted from 2017 VCAA Sample Exam Section B Q13

Key science skills

Question 15 (10 MARKS)

Students in a physics class are conducting an experiment to investigate the photoelectric effect. The metal surface is unknown to the students and they are tasked with finding out what it is. Their results are shown in the table below.

Stopping voltage (*V*)	**Frequency (Hz)**
0.25	6.0×10^{14}
0.60	7.0×10^{14}
0.90	8.0×10^{14}
1.50	9.0×10^{14}
1.90	10.0×10^{14}

a Plot their data on a set of axes and draw a line of best fit. (3 MARKS)

b Identify the independent and dependent variables in the experiment. (2 MARKS)

c Use the graph to estimate the threshold frequency. (1 MARK)

d Use the graph to estimate the value of Planck's constant obtained by the students. (2 MARKS)

e Using the included table, determine which metal is being used as a cathode in this investigation. (2 MARKS)

Element	**Work function (eV)**
Cesium	1.9
Europium	2.5
Magnesium	3.7
Manganese	4.1

Adapted from 2017 VCAA Sample Exam Section B Q17

11D WHAT THE PHOTOELECTRIC EFFECT MEANS

This lesson will expand upon our knowledge of the photoelectric effect. We will interpret the results of photoelectric experiment as evidence for the particle model of light and learn how to calculate the energy of individual photons (particles) of light.

11A Experimental design of the photoelectric effect	11B Changing intensity in the photoelectric effect	11C Changing frequency in the photoelectric effect	11D What the photoelectric effect means

Study design key knowledge dot points

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\ max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons
- describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect
- analyse the absorption of photons by atoms, with reference to:
  - the change in energy levels of the atom due to electrons changing state
  - the frequency and wavelength of emitted photons: $E = hf = \frac{hc}{\lambda}$

Key knowledge units

Why the wave model fails	4.2.3.1
Evidence for the particle-like nature of light	4.2.2.4
The energy of a photon	4.2.10.1

Formulas for this lesson

Previous lessons			New formulas	
9B	*	$v = f\lambda$	*	$E_{photon} = hf$
11C	*	$KE_{max} = hf - \phi$		$E_{photon} = \frac{hc}{\lambda}$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

discrete limited to certain values (not continuous)

particle a theoretical object that is discrete and has a defined location

photon a particle of light with a discrete amount of energy

Why the wave model fails 4.2.3.1

OVERVIEW

The wave model of light fails to predict important results of the photoelectric experiment. This will lead us to reconsider our understanding of light.

THEORY DETAILS

The wave model makes **three incorrect predictions** about the photoelectric effect.

Table 1 The incorrect predictions of the wave model of light compared with the actual observations

What the wave model predicts	What is actually observed
A time delay between when light is turned on and when a current is measured	Negligible time delay
Any frequency of light would produce a photocurrent given enough time	Existence of the threshold frequency
The kinetic energy of electrons would depend on the intensity (amplitude) of light	Maximum kinetic energy of emitted electrons is independent of intensity

Understanding the wave model's incorrect predictions

The reasons the wave model makes these incorrect predictions are explained in this section.

1. Time delay

Fundamentally, a wave is a continuous distribution of energy. So it was predicted that when a wave hits an electron its energy would be absorbed by the electron until the electron has enough energy to escape the metal plate. A time delay would be observed over the time it takes for an electron to absorb enough energy to be emitted.

2. Any frequency can produce a photocurrent

A wave's energy is determined by both its frequency and intensity (amplitude). As a light wave is absorbed by an electron its energy would gradually transfer to the electron. Hence, even though a lower frequency wave carries less energy, all frequencies of light could cause an electron to be emitted (producing a current) if given sufficient time and the light is intense enough.

3. Kinetic energy of electrons depends on intensity (amplitude) of light

The wave model predicts that the light energy is proportional to intensity. Greater intensity should transfer more energy to the electrons. Hence, it is predicted that the intensity should affect the kinetic energy of photoelectrons.

USEFUL TIP

'Intensity' is often a better word to use than 'amplitude' to describe brightness as it can be used when referring to both a wave or a particle.

Problem solving process

When asked a question about why the wave model fails to explain the photoelectric effect:

1 State that the wave model's predictions do not match experimental results.
2 Identify what the wave model predicts.
3 Explain what the actual corresponding observation is.

Evidence for the particle-like nature of light 4.2.2.4

OVERVIEW

A photon represents a particle of light. A discrete particle interpretation of frequency and intensity of light sufficiently explains the photoelectric effect.

THEORY DETAILS

In order to understand the particle model we must first understand that a particle is any object with a defined location. A photon is modelled as a particle of light and it has a discrete amount of energy. By interpreting frequency and intensity of light in line with a particle model, we can correctly predict the results of the photoelectric effect.

Table 2 Wave and particle interpretations of frequency and intensity

	Wave interpretation	Particle interpretation
Frequency (colour)	The number of wave cycles completed per unit of time	A property of individual photons related to the photon's energy
Intensity (brightness)	The amplitude of the wave	A measure of the number of incident photons per unit of time (assuming the frequency is held constant)

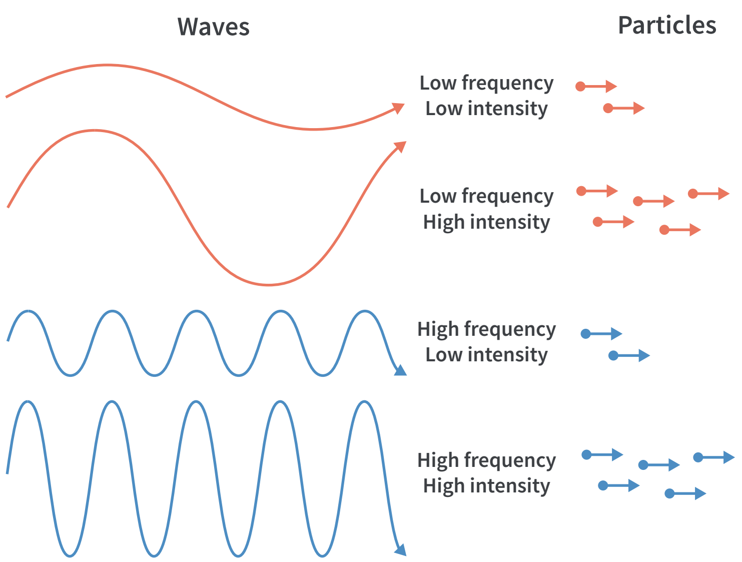


Figure 1 A visual comparison between the particle and wave models of light. Blue light has a higher frequency than red light.

Understanding the particle model's correct predictions

The reasons the particle model correctly predicts the results that the wave model failed to predict are explained in this section.

1. Negligible time delay

A photon's energy is discrete. When a photon reaches an electron the entire photon's energy is absorbed instantly, rather than accumulating over time. If the photon has sufficient energy then the electron will be emitted. If the photon does not have enough energy then the electron will not be emitted at all.

2. Threshold frequency

A photon's energy is discrete and proportional to its frequency. An electron will absorb a single photon, and if that photon's energy is less than the work function no electrons will be emitted. Hence there is a certain frequency (the threshold frequency) below which the incident light cannot produce a current.

3. Electron kinetic energy does not depend on intensity

An electron will absorb and gain the energy of a single photon. Intensity is a property of a group of photons rather than an individual photon which means the intensity does not affect the kinetic energy of individual electrons. The energy of a single photon depends on frequency only. Hence, the kinetic energy of the electron that absorbs the photon will also depend on the photon's frequency (according to $KE_{max} = hf - \phi$ as seen in lesson 11C) but not the intensity of the light.

Note that the independence of electron kinetic energy from intensity assumes a constant frequency.

USEFUL TIP

Wave-particle duality claims light demonstrates both wave and particle behaviours depending on the situation. Therefore it is important never to state that light 'is' a wave or 'is' a particle. Instead, state that **light 'can behave/be modeled'** as a wave or particle.

Problem solving process

When asked a question about why the photoelectric effect supports the particle model:

1. State that the particle model correctly predicts the experimental results.
2. Identify an observation of the photoelectric effect.
3. Describe the particle interpretation of the relevant property of light.
4. Explain how that interpretation supports the observations of the experiment.

The energy of a photon 4.2.10.1

OVERVIEW

A photon is modelled as a particle of light with a discrete amount of energy which can be calculated if the frequency or wavelength of the photon is known.

THEORY DETAILS

Each photon has a discrete amount of energy. The energy of a photon depends on the frequency (or wavelength) of the light according to the following equation. $E_{photon} = hf$

> **E_{photon} = photon energy (J or eV), h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s), f = light frequency (Hz)**

The photon energy equation may be recognisable as the first part of the equation $KE_{max} = hf - \phi$. We can rewrite the equation as $KE_{max} = E_{photon} - \phi$.

Given $c = f\lambda$, the photon energy also takes the following form.

> $$E_{photon} = \frac{hc}{\lambda}$$
> **E_{photon} = photon energy (J or eV), h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s), c = speed of light (3.0×10^{8} m s^{-1}), λ = wavelength (m)**

1 **Worked example**

A laser shines monochromatic light with a wavelength of 30 nm.

a What is the energy of each photon in joules?

b If the laser power output is 4.0×10^{-2} J s^{-1}, calculate the number of photons being produced each second.

a Wavelength: $\lambda = 30 \times 10^{-9}$ m

To obtain an answer in joules we must use $h = 6.63 \times 10^{-34}$ J s for Planck's constant.

Speed of light: $c = 3.0 \times 10^{8}$ m s^{-1}

$$E_{photon} = \frac{hc}{\lambda}$$

Substitute values into the equation.

$$E_{photon} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{30 \times 10^{-9}} = 6.63 \times 10^{-18} \text{ J}$$

The energy of each photon is 6.6×10^{-18} J to two significant figures.

b $E_{photon} = 6.63 \times 10^{-18}$ J from previous question

$E_{total} = 4.0 \times 10^{-2}$ J s^{-1}

Let n be the number of photons per second.

$E_{total} = n \times E_{photon}$

$4.0 \times 10^{-2} = n \times 6.63 \times 10^{-18}$

$n = 6.0 \times 10^{15}$ photons per second.

Theory summary

- The wave model **incorrectly** predicts
  - a time delay.
  - any frequency can emit electrons.
  - electron kinetic energy is related to light intensity.
- The particle model correctly predicts the results of the photoelectric experiment:
  - No time delay
  - Existence of the threshold frequency
  - Electron kinetic energy is independent of light intensity
- The particle model of light states that
  - frequency is a property of individual photons that determines the photon's energy.
  - for a given frequency, intensity is a measure of the number of incident photons per unit of time.
- A photon's energy can be calculated by $E = hf$ and $E = \frac{hc}{\lambda}$.

KEEN TO INVESTIGATE?

YouTube video: OpenMind – The Photoelectric Effect
https://youtu.be/0b0axfyJ4oo

11D Questions

THEORY REVIEW QUESTIONS

Question 1

A particle can be best described as

A a really small object.

B a discrete object with a defined location.

C an electron.

D a discrete bundle of energy.

Question 2

Which result of the photoelectric experiment does the wave model **not** predict?

A Kinetic energy of electrons depends on the work function.

B Only light above a certain frequency can produce a current.

C The total amount of energy in light depends on frequency.

D The current depends on the intensity of light.

Question 3

Complete the table using the descriptions and predictions provided below.

Descriptions

D1 The number of photons per unit time

D2 Discrete

D3 The amplitude

D4 A property of individual photons that determines energy

D5 Continuous

D6 Number of cycles per unit time

Predictions

P1 The existence of a threshold frequency

P2 A time delay

P3 For a given frequency, intensity determines electron kinetic energy

P4 For a given frequency, intensity has no effect on electron kinetic energy

P5 Negligible time delay

P6 Any frequency can produce a current

		Wave	Particle
Energy Distribution	Description		
	Prediction		
Frequency	Description		
	Prediction		
Intensity	Description		
	Prediction		

EXAM-STYLE QUESTIONS

This lesson

Question 4 (3 MARKS)

James Clerk Maxwell argues that the wave model of light can fully explain the results of the photoelectric experiment. Max Planck disagrees. Who is correct? Use one observation from the photoelectric experiment to support your answer.

Question 5 (2 MARKS)

A photon has a frequency of 4.0×10^{14} Hz. Calculate its energy in joules.

Question 6 (2 MARKS)

Christiaan Huygens is performing the photoelectric experiment using light with a frequency of 6×10^{14} Hz but measures zero current. He then doubles the brightness of his light source but still observes no current. How does Huygens' observation support the particle model but not the wave model?

Question 7 (3 MARKS)

a An electron has a kinetic energy of 160 eV, and emits a photon with a frequency of 3.80×10^{15} Hz. What is the kinetic energy of the electron after emitting the photon, in electron-volts? (2 MARKS)

b What is the wavelength of the photon? Give your answer to the nearest nanometre. (1 MARK)

Question 8 (3 MARKS)

While conducting a photoelectric experiment with a particular metal surface, Erwin Schrödinger finds that he observes the same maximum kinetic energy vs frequency graph for two different values of light intensity. Explain what this result reveals about the nature of light.

Question 9 (2 MARKS)

An electron loses 15 eV of kinetic energy by emitting a photon. Calculate the frequency of the emitted photon.

Question 10 (3 MARKS)

Which of the following does the wave model fail to predict? Justify your answer.

Observation 1: Incident light can liberate electrons when shone on a metal plate.

Observation 2: The photocurrent depends on the intensity of incident light.

Observation 3: There is negligible time delay between when the light shines on the plate and when a photocurrent is observed.

Adapted from 2010 VCAA Exam 2 Section A AoS 2 Q2

Question 11 (4 MARKS)

Albert Einstein won the Nobel prize in 1921 for the photoelectric experiment. Identify two results from this experiment that support the particle model of light. Explain why these conclusions support the particle model of light.

Previous lessons

Question 12 (1 MARK)

The string shown below has fixed ends.

Sketch the wave after it has been reflected once and indicate the direction of travel.

Question 13 (1 MARK)

Students are trying to determine the natural frequency of a string by forcing oscillation at various frequencies. How are students able to identify when resonance occurs?

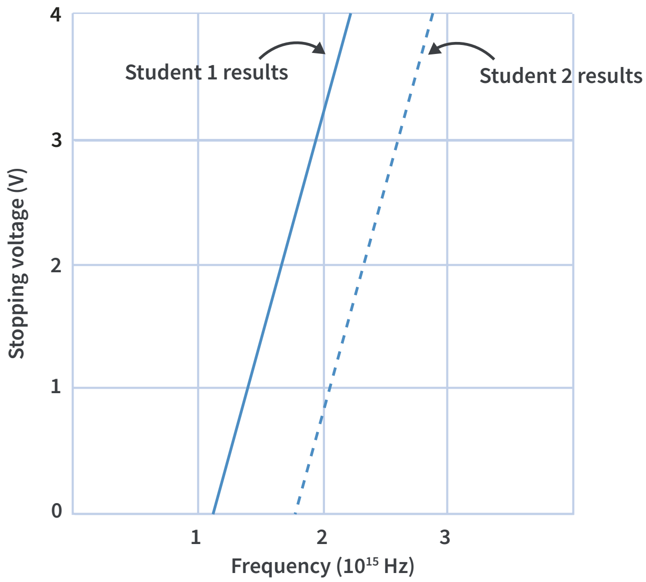
Question 14 (2 MARKS)

Starting from rest, Enrico Fermi skis down a 150 metre high mountain. What is the magnitude of his speed when he reaches the bottom of the slope? Ignore the effect of resistance forces.

Key science skills

Question 15 (3 MARKS)

Two students perform the photoelectric experiment for a range of frequencies, both using a zinc plate. They compared their results and found different stopping voltage vs frequency graphs. Explain which type of experimental error has occurred, and why might it have occurred.



CHAPTER 11 QUESTIONS

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

An experiment was set up to test the effect of changing photon energy on the photocurrent using a zinc plate as the metal cathode.

Which of the following is an independent variable in this photoelectric experiment?

A Frequency of light **B** Cathode **C** Metal **D** Photocurrent

Question 2

Which of the following observations from the photoelectric effect does not provide evidence for the particle nature of light?

A No time delay

B Electron kinetic energy does not depend on intensity

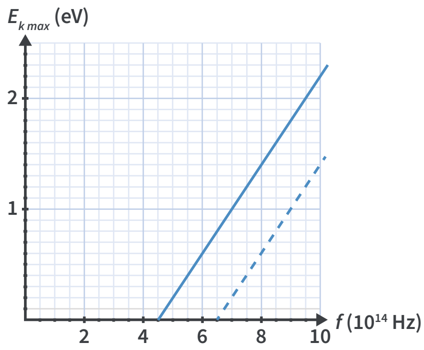
C Greater intensity leads to a larger photocurrent

D Existence of a threshold frequency

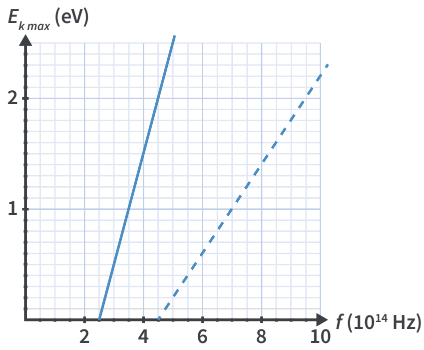
Question 3

A kinetic-energy frequency graph for a particular photoelectric experiment is drawn with a solid line. The experiment is then repeated with higher intensity light and the metal surface is replaced with one that has a lower work function. The new results are recorded with a dotted line on the same set of axes. Which option best represents the student's results?

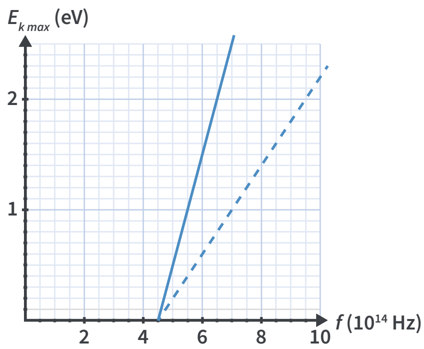
A



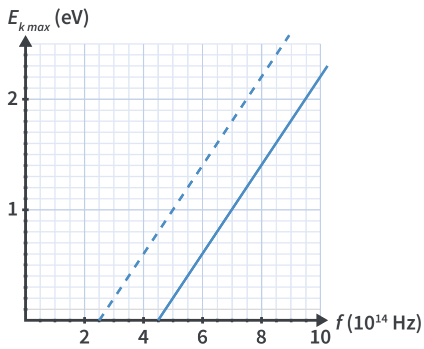
B



C



D



Adapted from 2018 VCAA Exam Section A Q17

Question 4

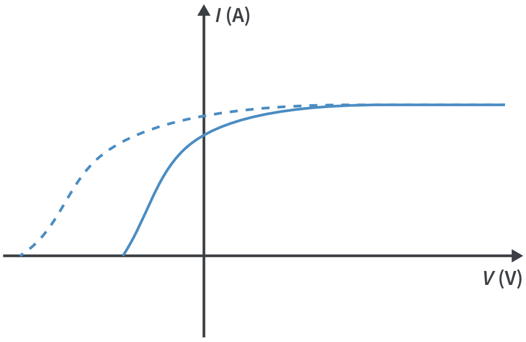
Photoelectrons are released with a maximum kinetic energy of 4.0 eV. What is the stopping voltage?

A -6.4×10^{-19} J
B 6.4×10^{-19} J
C 2.5×10^{19} V
D 4.0 V

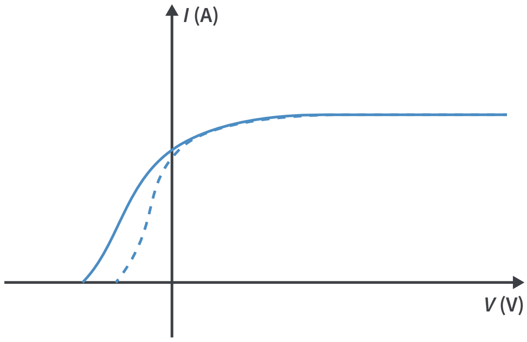
Question 5

Students conduct a photoelectric experiment. They map their first results on a current-voltage graph with a solid line. The students repeat the experiment with light that has a higher intensity and lower frequency (but it is still above the threshold frequency). They plot the new results on the same axes with a dotted line. Which of the following is closest to their results?

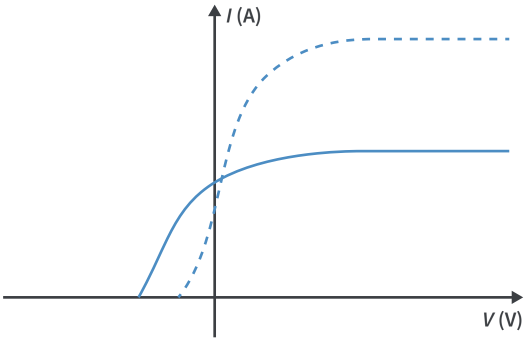
A



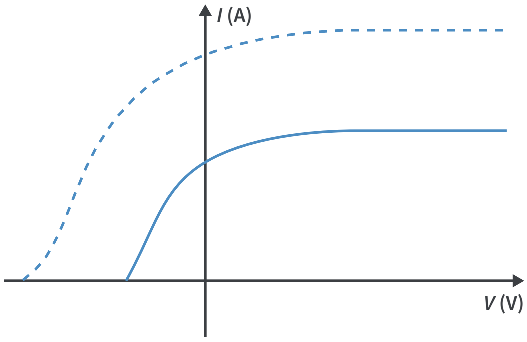
B



C



D



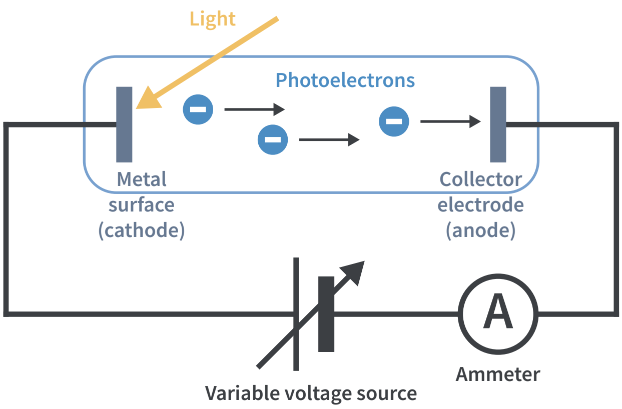
SECTION B

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 (8 MARKS)

Amelia, Lara and Zadie are conducting the photoelectric experiment to determine how changing the frequency of a light source affects the kinetic energy of photoelectrons.



a For the first part of the experiment the students use a potassium cathode. The students placed their results in a table.

Frequency (Hz)	Stopping voltage (V)
5.8×10^{14}	0.1
6.5×10^{14}	0.5
7.5×10^{14}	0.7
8.0×10^{14}	1.1
9.5×10^{14}	1.5

Plot the results on a set of axes and draw a line of best fit to show the maximum kinetic energy of the emitted electrons (in electron-volts) versus frequency falling on the metal plate. (3 MARKS)

Adapted from VCAA 2011 Exam 2 Section A AoS 2 Q6

b Use the graph to find the work function for potassium that the students would obtain. (1 MARK)

c Use the graph to calculate the value of Planck's constant that the students would obtain from this data. (2 MARKS)

d The students replace the potassium cathode with a different metal that has a work function of 1.8 eV. An electron is ejected from this plate with a kinetic energy of 6.56×10^{-19} J. Calculate the energy (in electron-volts) of the photon that was absorbed by the electron. (2 MARKS)

Question 7 (6 MARKS)

a Legolas and Gimli cannot remember the energy of the light used in a photoelectric experiment and need their lab partner Aragorn to help calculate it. It is known that the work function of the metal used was 7.36×10^{-19} J and the stopping voltage was 1.4 V. Aragorn obtained an answer of 3.2 eV. Is this correct? Show your working. (3 MARKS)

b Tauriel conducts a photoelectric experiment using a zinc plate and light with a frequency of 6.0×10^{14} Hz. She allows the light to shine for a long time and increases the intensity but no photocurrent is measured. Explain how Tauriel's observations support a particle model of light but do not support a wave model. (3 MARKS)

Adapted from 2019 VCAA NHT Exam Section B Q16c

Question 8 (9 MARKS)

Aliya performs a photoelectric experiment using a metal with a work function of 3.0 eV and a variable electrode potential.

a In her first experiment, the light incident upon the plate is of high enough energy that a steady stream of photoelectrons is leaving the plate. Aliya increases the reverse potential from zero to a large value.

Describe, with justification, the photocurrent as the reverse potential is increased from zero. (3 MARKS)

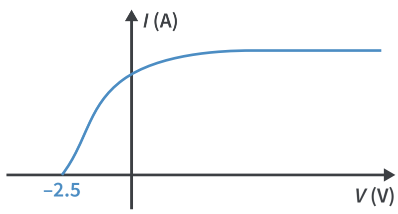
b Aliya stops increasing the reverse potential when it reaches 5.0 V as no photocurrent is detected. Calculate the maximum kinetic energy of electrons being ejected in joules. (2 MARKS)

c Calculate the minimum frequency photon that Aliya needs to release an electron. (2 MARKS)

d Calculate the frequency of light for which Aliya measured a stopping voltage of 5.0 V. (2 MARKS)

Question 9 (11 MARKS)

The photocurrent-electrode potential curve for a photoelectric experiment is shown. The work function of the metal surface is 1.8×10^{-19} J.



a Copy the graph and draw the resultant curve if the experiment was repeated with lower intensity incident light of the same frequency. Use a dashed line for the new curve. (2 MARKS)

b Identify which feature of both curves in part **a** provides evidence for the particle model of light but not the wave model. Explain your answer. (4 MARKS)

c Explain why the graph is a flat, straight line for large positive values of electrode potential. (2 MARKS)

d Calculate the wavelength of the incident light. (3 MARKS)

Adapted from 2017 VCAA NHT Exam Section A Q18

Question 10 (4 MARKS)

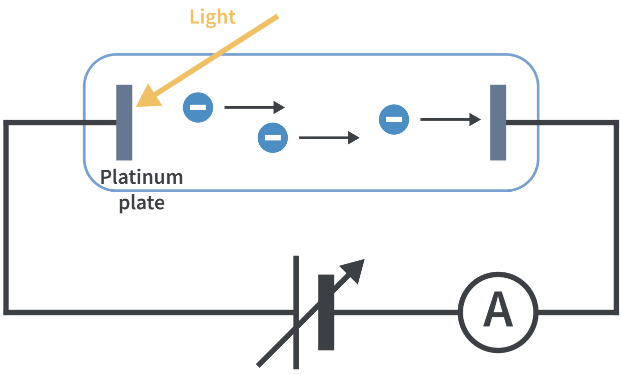
a Evaluate the following statement. 'When photoelectrons are emitted from a metal surface due to light of a single frequency, all photoelectrons have the same kinetic energy.'

Justify your answer. (2 MARKS)

b Within the photoelectric experiment, describe the effect on photocurrent when the frequency of incident light is decreased from well above the threshold frequency to the threshold frequency, and then to well below the threshold frequency. (2 MARKS)

Question 11 (7 MARKS)

Lily has set up the following circuit.



Lily measures the speeds of the electrons being ejected from the metal cathode with zero electrode potential applied across the plates. The greatest speed was 1.22×10^6 m s^{-1} when using incident light of frequency 1.96×10^{15} Hz.

a Find the magnitude of the voltage that would need to be applied to the circuit to stop the photocurrent. (2 MARKS)

b Calculate the work function of platinum, in joules. (2 MARKS)

c They repeat the experiment with a plate of zinc which has a work function of 4.33 eV. Find the longest wavelength of a photon that can be used to release a photoelectron. (3 MARKS)

UNIT 4 AOS 2, CHAPTER 12

The wave-particle duality of light and matter

12

Key knowledge

- investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to limitations of imaging using light
- interpret electron diffraction patterns as evidence for the wave-like nature of matter
- distinguish between the diffraction patterns produced by photons and electrons
- calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- compare the momentum of photons and of matter of the same wavelength including calculations using: $p = \frac{h}{\lambda}$
- explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- interpret spectra and calculate the energy of absorbed or emitted photons: $\Delta E = hf$
- analyse the absorption of photons by atoms, with reference to:
  - the change in energy levels of the atom due to electrons changing state
  - the frequency and wavelength of emitted photons: $E = hf$ and $E = \frac{hc}{\lambda}$
- describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter
- interpret the single photon/electron double slit experiment as evidence for the dual nature of light/matter
- explain how diffraction from a single slit experiment can be used to illustrate Heisenberg's uncertainty principle
- explain why classical laws of physics are not appropriate to model motion at very small scales
- compare the production of light in lasers, synchrotrons, LEDs and incandescent lights

Image: katjen/Shutterstock.com

12A COMPARING LIGHT AND MATTER

The 20th century brought about a fundamental shift in how we understand the behaviour of atomic and subatomic particles. This development is called quantum theory. This theory was necessary as the classical models for the universe continued to fail to model the interactions of small objects.

12A Comparing light and matter	12B Heisenberg's uncertainty principle	12C Absorption and emission spectra	12D Production of light

Study design key knowledge dot points

- investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to limitations of imaging using light
- interpret electron diffraction patterns as evidence for the wave-like nature of matter
- distinguish between the diffraction patterns produced by photons and electrons
- calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- compare the momentum of photons and of matter of the same wavelength including calculations using: $p = \frac{h}{\lambda}$
- interpret the single photon/electron double slit experiment as evidence for the dual nature of light/matter

Key knowledge units

Matter waves: electrons diffract	4.2.4.1 & 4.2.6.1
The diffraction of light	4.2.1.1
Photons and electrons in the double slit experiment	4.2.12.1
Comparing the momentum and diffraction of electrons and photons	4.2.7.1 & 4.2.5.1

Formulas for this lesson

Previous lessons		New formulas
3A	* $p = mv$	* $\lambda = \frac{h}{p}$
9G	$Diffraction \propto \frac{\lambda}{w}$	* $p = \frac{h}{\lambda}$
11C	* $E_{photon} = hf = \frac{hc}{\lambda}$	$E_{photon} = pc$

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Definitions for this lesson

de Broglie wavelength the wavelength associated with a particle due to its momentum

wave-particle duality the concept of light and matter exhibiting both wave behaviours and particle behaviours depending on the context

Matter waves: electrons diffract 4.2.4.1 & 4.2.6.1

OVERVIEW

Although electrons are typically modelled as particles, when they pass through small gaps, wave-like diffraction patterns emerge. This observation led to the discovery of the de Broglie wavelength for matter, which is dependent on momentum.

THEORY DETAILS

If we propel electrons through a small gap, like the space between atoms in a crystal lattice, a diffraction pattern appears (see Figure 1). The first experiment to demonstrate this brought about confusion as it proved that matter, which was considered to demonstrate only particle properties, can behave like waves at very small scales. This is called the **wave-particle duality**.

It is important to understand that 'waves' and 'particles' are just models for the way certain physical objects behave. Therefore, it is best to describe electrons as **demonstrating the properties of both particles and waves**.

Given that electrons can behave like waves, a French physicist named Louis de Broglie hypothesised (and it was later proven) that electrons must have a wavelength which is related to the momentum of the particle and Planck's constant. Although large objects do not exhibit measurable wave-like properties, all objects have a de Broglie wavelength. Note that the de Broglie wavelength does **not** imply that particles of matter follow the path of a wave. Instead, the de Broglie wavelength is a property of the matter which determines to what extent it exhibits wave behaviour such as diffraction and interference.

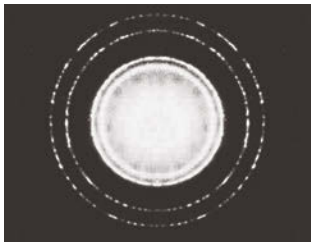


Figure 1 Diffraction pattern of electrons through a crystal lattice

$$\lambda = \frac{h}{p}$$

λ = de Broglie wavelength (m), p = momentum (kg m s^{-1}), h = Planck's constant (6.63×10^{-34} J s)

It is important to recognise that Planck's constant must take the value 6.63×10^{-34} J s in this formula because the wavelength and momentum both use SI units. It cannot take the value 4.14×10^{-15} eV s.

1 **Worked example**

Your uncle Bob is running his first lap of the block since 1999. He has a mass of 80 kg and is running at a speed of 4.0 m s^{-1}.

a **Calculate the de Broglie wavelength of your uncle Bob.**

b **Use the answer to explain why uncle Bob does not exhibit measurable diffraction as he runs through a doorway.**

a As $\lambda = \frac{h}{p}$, we need to find Bob's momentum.

$p = mv \ \therefore p = 80 \times 4.0 = 320$ kg m s^{-1}

Substitute this into the de Broglie equation and using the SI unit value of Planck's constant

$h = 6.63 \times 10^{-34}$ J s.

$\lambda = \frac{h}{p} \ \therefore \lambda = \frac{6.63 \times 10^{-34}}{320} = 2.1 \times 10^{-36}$ m

b Uncle Bob's de Broglie wavelength is so small (many orders of magnitude smaller than a doorway) that diffraction will be insignificant.

The diffraction of light 4.2.1.1

OVERVIEW

Light, like mechanical waves, can diffract through apertures or around bends. It follows the same principles of diffraction understood from lesson 9G.

THEORY DETAILS

In chapter 10 we established that light exhibits the wave property of diffraction through our discussion of the double slit experiment. The diffraction of light follows the same principle that we understand for mechanical waves: diffraction $\propto \frac{\lambda}{w}$ (see Figure 2).

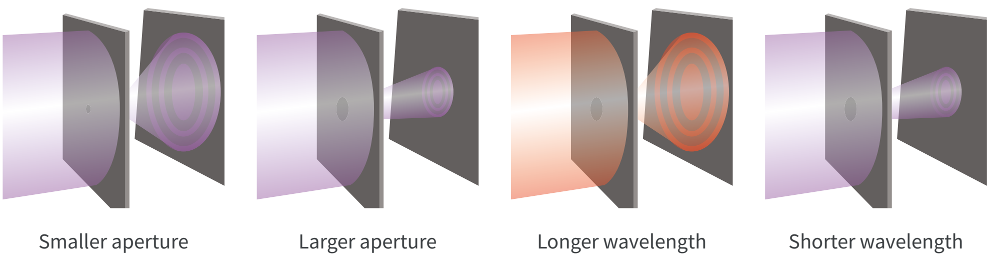


Figure 2 Demonstration of shifting wavelength and aperture size impacting the size of the diffraction pattern.

As shown in Figure 2, the diffraction of light is directly proportional to wavelength and inversely proportional to aperture width – like mechanical waves.

Photons and electrons in the double slit experiment 4.2.12.1

OVERVIEW

If we set up a double slit experiment using individual photons or electrons instead of a beam of light, an interference pattern occurs. This provides strong evidence for the dual wave-particle nature of small objects.

THEORY DETAILS

When single photons/electrons are sent through the slits one at a time, each one creates a single spot on the screen. This is as expected for single particles. However, **over time** the stream of single particles causes an interference pattern to appear on the screen behind (see Figure 3). As we know that only one particle is traveling at a time, it cannot be interfering with other particles. Hence, the individual electron can be considered to demonstrate the wave properties of diffraction and interference

How this provides evidence for wave-particle duality

- A single electron or photon leaves the source with **particle-like** discreteness and creates a single discrete spot on the screen.
- The interference pattern, which occurs **over time**, is a **wave property**.

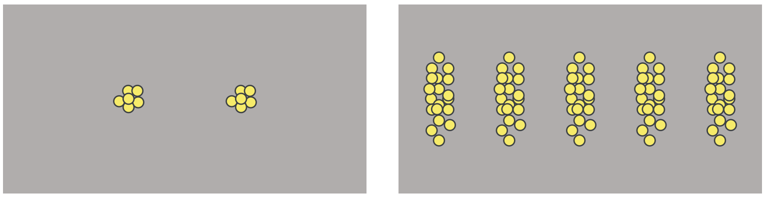


Figure 3 The expected and actual results of the double slit experiment when performed with photons and electrons

Comparing the momentum and diffraction of electrons and photons 4.2.7.1 & 4.2.5.1

OVERVIEW

Photons, unlike electrons, are astonishing as they can have momentum without mass. This changes how we calculate their momentum. One way to do this is to compare the diffraction patterns of electrons and photons of the same de Broglie wavelength. This allows us to calculate their momentum.

THEORY DETAILS

Momentum

Experiments have shown that photons have momentum even though they do not have mass. 'Compton scattering' is key evidence for this, but it is beyond the scope of this course. As such we **must not** use the traditional momentum equation, $p = mv$, for photons. If we transpose the de Broglie wavelength equation, $\lambda = \frac{h}{p}$, we find an expression for momentum that does not rely upon mass: $p = \frac{h}{\lambda}$. By combining this with the equation $E_{photon} = \frac{hc}{\lambda}$ from lesson 11D, we can derive a relationship between the energy and the momentum of a photon.

$$E_{photon} = pc$$

E_{photon} = photon energy (J), p = momentum (kg m s^{-1}), c = speed of light (3.0×10^8 m s^{-1})

Diffraction

As covered in lesson 9G, the extent of diffraction is determined by the wavelength and the gap width (diffraction $\propto \frac{\lambda}{w}$). Hence, when electrons and photons with the same wavelength (and momentum) diffract through the same gaps, the diffraction pattern will be the same (see Figure 4).

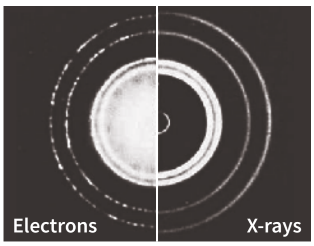


Figure 4 Electrons and X-rays with the same fring spacing

USEFUL TIP

In general, when electrons and photons produce the same diffraction pattern for a given gap width, the **energy** of each photon will be **different** to the kinetic energy of each electron. If we know the diffraction patterns are the same then our (only) conclusion should be that the wavelength (and momentum) of electrons is the same as that of the photons.

Table 1 A table of useful equations sorted by the types of particles that can be used with them. Of these equations, $E_{ph} = hf = \frac{hc}{\lambda}$ is the only equation which can take both values of Planck's constant.

Photons	Both	Matter/electrons
$E_{ph} = hf = \frac{hc}{\lambda}$	$p = \frac{h}{\lambda}$	$p = mv$
$E_{ph} = pc$	$\lambda = \frac{h}{p}$	$p = \sqrt{2m\,KE}$
$p = \frac{hf}{c}$		$KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}$

2 Worked example

An X-ray and a ray of electrons are shone through a lattice and the resulting diffraction pattern exhibits the same fringe spacing.

a **Given that each electron has a momentum of 2.50×10^{-23} kg m s^{-1}, calculate the energy of each X-ray photon.**

b **The X-ray emitted is changed so that each photon has an energy of 6.00×10^{-16} J. Calculate the speed of electrons which would produce the same pattern.**

c **Calculate the wavelength of the electrons used by the electron gun from part b.**

a "Same fringe spacing" tells us that the momentum of the X-rays is the same as that of the electrons.

Since X-rays are photons, we need to use equations applicable to photons.

$p = \frac{E}{c}$ $\therefore 2.50 \times 10^{-23} = \frac{E}{3.0 \times 10^{8}}$

$E = 7.5 \times 10^{-15}$ J

b $p = \frac{E}{c}$ $\therefore p = \frac{6.00 \times 10^{-16}}{3.0 \times 10^{8}} = 2.0 \times 10^{-24}$ kg m s^{-1}

$p = mv$ $\therefore 2.0 \times 10^{-24} = 9.1 \times 10^{-31} \times v$

$v = 2.2 \times 10^{6}$ m s^{-1}

c Take momentum from the last question and use the SI units value of Planck's constant.

$p = \frac{h}{\lambda}$ $\therefore 2.0 \times 10^{-24} = \frac{6.63 \times 10^{-34}}{\lambda}$

$\lambda = 3.3 \times 10^{-10}$ m

Theory summary

- Electron diffraction provides evidence for wave-particle duality of matter.
- A particle's wavelength can be described using the de Broglie equation: $\lambda = \frac{h}{p}$.
- Just like other waves, the extent of diffraction of light and electrons depends on the relationship between the wavelength and the size of the aperture $\left(\text{diffraction} \propto \frac{\lambda}{w}\right)$.
- The double slit experiment with single electrons and photons supports wave particle duality.
  - It exhibits the wave properties of diffraction and interference.
  - It exhibits the particle property of discreteness as each photon or electron produces a single spot on the screen.
- When the diffraction patterns of photons and electrons in the same experiment are the same, we can equate the wavelength (or momentum) of the photons with that of the electrons. We should **not** equate energies.

KEEN TO INVESTIGATE?

Hyperphysics 'Davisson-Germer Experiment'
http://hyperphysics.phy-astr.gsu.edu/hbase/DavGer.html#c1

YouTube video: Clover Learning – Compton Scattering
https://youtu.be/G1xEF5r69qo

YouTube video: PBS Space Time – How the Quantum Eraser Rewrites the Past
https://youtu.be/8ORLN_KwAgs

YouTube video: 'PBS Space Time – The Quantum Experiment that Broke Reality'
https://youtu.be/p-MNSLsjjdo

YouTube video: The Science Asylum – Momentum Does Not Require Mass
https://youtu.be/LoadZQkrfcQ

12A Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following objects, when in motion, has a wavelength?

A Electrons

B Tennis ball

C You

D All of the above

Question 2

Which properties do matter and electromagnetic waves share?

A The ability to diffract around objects

B They can interfere causing constructive and destructive interference.

C The ability to diffract through apertures

D All of the above

Question 3

Which of the following best describes the results of the single photon/electron double slit experiment?

A Each photon/electron creates a diffraction pattern.

B Over time, the photons/electrons land in two distinct bands corresponding to the two slits.

C Each photon/electron creates a single spot on the screen but, over time, these spots form an interference pattern.

D All the photons/electrons land on the same spot on the screen.

Question 4

Why was the single electron double slit experiment important to the theory of wave-particle duality?

A It was the same experiment that Young ran on light, proving that electrons are always waves.

B The results proved that electrons were particles.

C The results proved that electrons moved at the speed of light.

D The results proved that electrons displayed both wave and particle properties.

Question 5

Photons and then electrons of the same wavelength are used in a double slit experiment. How does the size of the electron fringe spacing compare with that of the photons?

A As photons travel at the speed of light, the photon diffraction pattern will be larger.

B The fringe spacing is the same.

C Whichever one has less energy will diffract more.

D As electrons are particles, they cannot diffract.

Question 6

Which of the following entries into the table gives the correct momentum equations for photons and electrons?

	Photon momentum	Electron momentum
A	$p = \frac{h}{\lambda}$	$p = mv$ & $p = \frac{h}{\lambda}$
B	$p = hf$	$p = mv$
C	$p = hf$ & $p = \frac{h}{\lambda}$	$p = mv$
D	$p = mv$ & $p = \frac{h}{\lambda}$	$p = \frac{h}{\lambda}$

EXAM-STYLE QUESTIONS

This lesson

Question 7 (4 MARKS)

The following diffraction pattern emerges when a beam of light is incident upon a pinhole.

a A beam with considerably shorter wavelength is used to repeat the experiment and a new diffraction pattern is produced with the same number of bright lines. Copy the diagram (for comparison) and draw the new pattern next to it. (2 MARKS)

b The experiment is repeated again with the original wavelength but with a smaller aperture. Describe and justify the change to the diffraction pattern. (2 MARKS)

Question 8 (2 MARKS)

Your friend Bailey has just finished his time at the CERN particle accelerator. In one of his final experiments he accelerated a single proton to 95% of the speed of light ($v = 2.85 \times 10^8$ m s^{-1}). Considering the mass of a proton is 1.67×10^{-27} kg, calculate the de Broglie wavelength of the proton. Ignore relativistic effects.

Question 9 (2 MARKS)

An electron gun is fired into a crystal lattice and the diffraction pattern is recorded and found to be the same diameter as a previous experiment where X-rays at 1.20×10^4 eV were shone through the same lattice. Calculate the wavelength of the electrons.

Question 10 (6 MARKS)

A photon has an energy of 50 keV.

a Calculate the magnitude of the momentum of this photon. (2 MARKS)

b Calculate the kinetic energy, in joules, of an electron which has the same momentum as the photon. (2 MARKS)

c What can be said about the diffraction patterns that would be formed if a photon and an electron with these momenta were fired through the same lattice? Justify your conclusion. (2 MARKS)

Question 11 (2 MARKS)

The Joker's lair uses an electron gun diffraction pattern as a key and Batman knows the required wavelength to unlock the lair is 0.20 nm. However, Batman only has his X-ray gun with him. Calculate what energy X-ray is required to unlock the door in electron-volts.

Question 12 (3 MARKS)

Explain how the single-electron double slit experiment provides evidence for wave-particle duality of matter.

Question 13 (3 MARKS)

When electrons from a particular electron gun are diffracted through a silicon lattice, the same diffraction pattern occurs as when X-Ray photons of 1.38×10^{-14} J pass through through the same lattice. At what speed are the electrons leaving the gun?

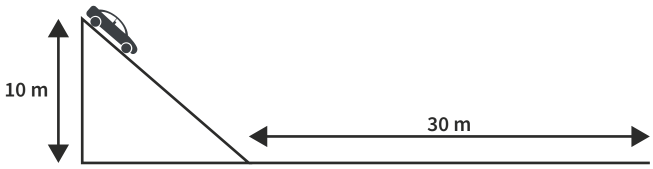
Question 14 (3 MARKS)

Students are setting up diffraction patterns using electron guns and photon beams. Sam hypothesises that if the energy of the electrons and photons were the same, the same diffraction pattern would emerge. Eva disagrees and suggests that as long as the wavelengths are the same, the diffraction pattern will be identical.

Evaluate the two students' claims.

Previous lessons

Question 15 (2 MARKS)



A car is rolling down a hill from rest. Calculate the magnitude of the velocity of the 1000 kg car 30 m further along the track assuming no friction.

Question 16 (3 MARKS)

Ariel walks down a hallway and hears a song coming from an open door on the side of the hallway, but can only hear the bass. As she gets closer to the door, she starts to hear the higher frequencies as well.

Explain her experience of the sound.

Key science skills

Question 17 (5 MARKS)

Your class has just recorded an experiment mapping the velocity of electrons, v, incident on a metal lattice to the size of the fringe spacing, Δx, in the diffraction pattern created.

Experiment	Δx (10^{-3} m)	v (10^6 m s^{-1})
1	3.64	1.00
2	2.43	1.50
3	1.82	2.00
4	1.46	2.50
5	1.21	3.00

Plot a graph of the fringe spacing, Δx, on the horizontal axis against $\frac{1}{v}$ on the vertical axis. Include:

- A line of best fit
- A scale on each axis
- A label with units on each axis

12B HEISENBERG'S UNCERTAINTY PRINCIPLE

The smaller the particles we analyse, the more they deviate from our classical understanding of the world. How can photons have momentum without having mass? How can a particle also behave as a wave? The subatomic world exhibits 'weirdness' and Heisenberg's uncertainty principle presents a fascinating way of explaining some of this weirdness.

12A Comparing light and matter	12B Heisenberg's uncertainty principle	12C Absorption and emission spectra	12D Production of light

Study design key knowledge dot points

- explain how diffraction from a single slit experiment can be used to illustrate Heisenberg's uncertainty principle
- explain why classical laws of physics are not appropriate to model motion at very small scales

Key knowledge units

Heisenberg's uncertainty principle in the single slit experiment	4.2.13.1
Classical laws fail at very small scales	4.2.14.1

Formulas for this lesson

Previous lessons		**New formulas**
3A	* $p = mv$	No new formulas in this lesson
12A	* $\lambda = \frac{h}{p}$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

Heisenberg's uncertainty principle in the single slit experiment 4.2.13.1

OVERVIEW

Heisenberg's uncertainty principle offers an explanation for the wave-like diffraction of small particles such as electrons and photons.

THEORY DETAILS

Heisenberg's uncertainty principle states that there is an inherent uncertainty in the measurements of the position and the momentum of any physical object, and that these uncertainties are related. As momentum is a vector, the uncertainty in momentum leads to uncertainty in the direction that the particle is travelling. It is important to understand that Heisenberg's uncertainty principle is not related to the quality of the measuring devices being used. Instead, it is a physical limit.

Heisenberg developed an inequation to quantify this in relation to Planck's constant. The following formula does not need to be applied in this course, but it is helpful to properly understand the meaning of Heisenberg's uncertainty principle.

$$\Delta x \Delta p_x \geq \frac{h}{4\pi}$$

Δx = uncertainty in position in the x-direction, Δp_x = uncertainty in momentum in the x-direction, h = Planck's constant

As the right hand side of the equation, $\frac{h}{4\pi}$, is a constant, when we take a measurement which reduces the uncertainty in the position of a particle it will increase the uncertainty in the momentum of the particle. Similarly, a measurement which reduces the uncertainty in the momentum will increase the uncertainty in the position of the particle.

It is important to note that this uncertainty is directional:

- Uncertainty in the *x*-position impacts the uncertainty in the momentum only in the *x*-direction. That is $\Delta x \Delta p_x \geq \frac{h}{4\pi}$.
- Uncertainty in the *y*-position impacts uncertainty in the momentum only in the *y*-direction. That is, $\Delta y \Delta p_y \geq \frac{h}{4\pi}$.

Figure 1 shows electrons incident upon a small slit and a diffraction pattern on the screen behind the slit. Table 1 shows how Heisenberg's uncertainty principle can be used to explain this result.

Table 1 How the diffraction pattern in Figure 1 illustrates Heisenberg's uncertainty principle.

Stage	Explanation
1	We cannot measure the exact position of each electron or its exact momentum as it approaches the slit; there is uncertainty in both position and momentum.
2	The uncertainty in each electron's *y*-position is reduced to the width of the slit (since we are certain it passes through the slit). This increases its uncertainty in the momentum of the *y*-direction.
3	The uncertainty in the momentum in the *y*-direction means each electron could follow a path anywhere in the cone shape of the diagram. Over time, due to many electrons, this appears as a diffraction pattern.

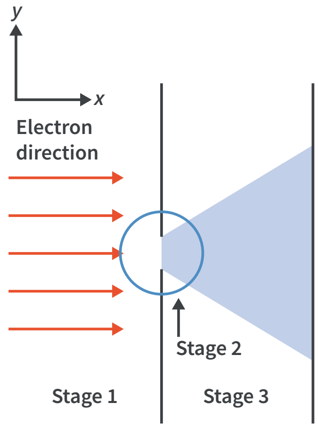


Figure 1 A beam of electrons incident on a single slit

Classical laws fail at very small scales 4.2.14.1

OVERVIEW

The laws of classical physics fail to describe the motion of very small particles because classical laws assume all measurements can have unlimited certainty and that particles and waves are distinct, rather than all objects having a dual nature.

THEORY DETAILS

The Heisenberg uncertainty principle explanation

If we evaluate the right-hand side of Heisenberg's inequation we have $\Delta x \Delta p_x \geq 5.28 \times 10^{-35}$ J s. For very small (subatomic) particles this leads to a significant amount of uncertainty in their position or momentum, relative to their small size and momentum. The classical laws of physics rely on certainty which means they cannot model motion at very small scales.

Heisenberg's uncertainty principle still applies at large scales but the confidence limit stipulated by Heisenberg's uncertainty principle is much less significant, due to the large values of momentum and the size of the objects. This means the classical laws do a sufficient job of predicting the behaviour of large objects.

The wave-behaviour explanation

From de Broglie's wave equation $\left(\lambda = \frac{h}{p}\right)$, we know that the wavelength of small objects (with a small mass and therefore small momentum) is large and the wavelength of large objects (with a large mass and momentum) is small. This means that the extent of wave behaviours (such as diffraction which depends on the $\frac{\lambda}{w}$ ratio) which a particle exhibits is much more significant for objects at very small scales. The classical laws of physics treat particles and waves as distinct (mutually exclusive) and therefore they cannot accurately model motion at very small scales.

THEORY SUMMARY

- Heisenberg's uncertainty principle states that it is physically impossible to measure both the position and the momentum of an object with unlimited certainty.
  - The greater the confidence in one measurement, the greater the uncertainty in the other measurement.
  - The relationship between the uncertainty in position and momentum is directional (uncertainty in position in the *x*-direction affects the uncertainty in momentum in the *x*-direction only).
- The limit in the certainty of measurements is significant for very small scales but it is negligible at larger scales.

- Classical laws of physics assume that all measurements can have unlimited certainty and that waves and particles are distinct.
  - At large scales these assumptions are appropriate.
  - At small scales these assumptions are not appropriate because uncertainty is significant compared to the size of the objects and the de Broglie wavelengths are large enough to cause significant wave behaviour.

KEEN TO INVESTIGATE?

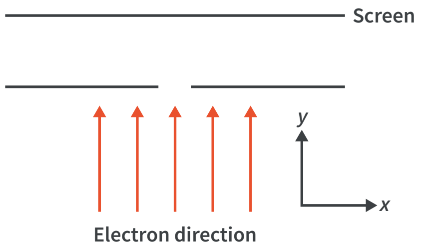
YouTube video: TED-Ed – What is the Heisenberg Uncertainty Principle?
https://youtu.be/TQKELOE9eY4

YouTube video: Veritasium – Heisenberg's Uncertainty Principle Explained
https://youtu.be/a8FTr2qMutA

12B Questions

THEORY REVIEW QUESTIONS

Question 1



A wide beam of electrons passes through a small slit. Which option correctly describes the direction in which the uncertainty in position is affected by the slit, and the change in uncertainty in position caused by passing through the slit?

	Direction of uncertainty affected by slit	Uncertainty in position
A	x	Decreased
B	x	Increased
C	y	Increased
D	y	Decreased

Question 2

A particle's y-momentum uncertainty is decreased when a measurement is taken. What else can be said about the particle?

A The x-momentum uncertainty is increased.

B The y-position uncertainty is increased.

C The y-position uncertainty is decreased.

D The x-momentum uncertainty is decreased.

Question 3

To which of these objects can the classical laws of physics appropriately be applied?

A An electron

B A photon

C A cricket ball

D All of the above

Question 4

To which of these objects does Heisenberg's uncertainty principle apply?

A A shoe

B A cell

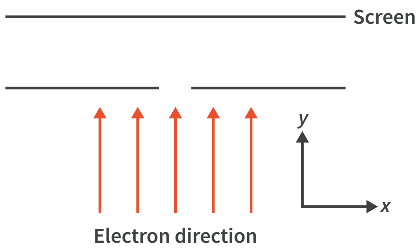
C An electron

D All of the above

EXAM-STYLE QUESTIONS

This lesson

Question 5



Electrons scatter as they pass through a slit. Using Heisenberg's uncertainty principle, we can explain the scattering by the uncertainty in the electrons'

A y-position affecting uncertainty in their x-momentum.

B y-position affecting uncertainty in their y-momentum.

C x-position affecting uncertainty in their y-momentum.

D x-position affecting uncertainty in their x-momentum.

Adapted from 2018 VCAA Exam Section A Q15

Question 6

Electrons are fired through a small circular hole in a screen. Which of these options is true when the electrons pass through the hole?

A The *x*-position uncertainty increases.

B The *x*- and *y*-position uncertainties increase.

C The uncertainty in momentum in the *y*-direction decreases.

D The uncertainties in momentum in the *x*- and *y*-directions increase.

Question 7 (3 MARKS)

With reference to the single slit experiment, explain how the diffraction of electrons illustrates Heisenberg's uncertainty principle.

Question 8 (4 MARKS)

Explain why we can not apply classical laws to very small scales, but we can to large scales:

a using the de Broglie wavelength of matter. (2 MARKS)

b using Heisenberg's uncertainty principle. (2 MARKS)

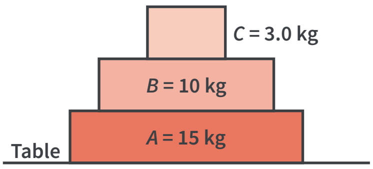
Question 9 (2 MARKS)

Tadhg and Alice are propelling electrons towards each other and want to analyse the collisions. Tadhg claims that we can use classical physics to analyse the collisions but Alice claims that this will not give accurate predictions.

Evaluate Tadhg and Alice's claims.

Previous lessons

Question 10 (4 MARKS)



a Draw a free body diagram representing the forces upon block *A* and label the arrows. You do not need to calculate the forces, but the length of the arrows should reflect their relative magnitudes. (2 MARKS)

b The table is removed and the blocks are sent into free fall. Taking gravity to be $g = 9.8$ m s^{-2}, what is the force on block *B* by block *A*. Justify your answer. (2 MARKS)

Adapted from 2011 VCAA Exam 1 Section A AoS 1 Q8

Question 11 (3 MARKS)

a It takes 8 minutes and 19 seconds, on average, for light to travel from the Sun to Earth. Calculate the average distance between the Sun and Earth. (2 MARKS)

b The sun emits photons over the full range of the electromagnetic spectrum. Sort the following types of electromagnetic waves from lowest frequency to highest frequency:

Ultraviolet, visible light, X-rays, gamma rays, microwaves. (1 MARK)

Key science skills

Question 12 (3 MARKS)

Davisson is using an electron gun to fire individual electrons at a single slit with a fixed width. Davisson changes one property (an independent variable) of the electrons and records the resulting diffraction pattern spacing.

a Identify a controlled variable. (1 MARK)

b Remembering the diffraction equation and de Broglie's equation for wavelength, what property of the electrons must be varied for the diffraction pattern spacing to be the dependent variable? Justify your answer. (2 MARKS)

12C ABSORPTION AND EMISSION SPECTRA

This lesson will introduce the quantised states of the atom through observations of absorption and emission spectra and show how this is a consequence of the wave properties of electrons.

12A Comparing light and matter	12B Heisenberg's uncertainty principle	12C Absorption and emission spectra	12D Production of light

Study design key knowledge dot points

- explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- interpret spectra and calculate the energy of absorbed or emitted photons: $\Delta E = hf$
- analyse the absorption of photons by atoms, with reference to:
  - the change in energy levels of the atom due to electrons changing state
  - the frequency and wavelength of emitted photons: $E = hf$ and $E = \frac{hc}{\lambda}$
- describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter

Key knowledge units

Absorption and emission spectra	4.2.8.1 & 4.2.9.1
Electron standing waves	4.2.11.1

Formulas for this lesson

Previous lessons		New formulas
11D	* $E = hf$	$E_{photon} = \Delta E$
11D	$E = \frac{hc}{\lambda}$	

(*Indicates formula, or a similar version, is on VCAA formula sheet)

absorption spectrum the specific set of frequencies of light that a material absorbs due to electron energy transitions

discrete limited to certain values (not continuous)

emission spectrum the specific set of frequencies of light that a material emits due to electron energy transitions

quantised see discrete

Absorption and emission spectra 4.2.8.1 & 4.2.9.1

OVERVIEW

Electrons exist in quantised (or discrete) energy levels around an atom that determine the discrete photon energies an atom can emit or absorb, as seen in its spectral lines. Metal vapour lamps produce light in the form of an emission spectra.

THEORY DETAILS

An absorption spectrum shows the discrete frequencies of light that a particular atom will absorb when the full spectrum of light is shone through it. The emission spectrum of an element is, in a sense, the opposite of its absorption spectrum. When an atom is excited (has enough energy) it will emit the same discrete wavelengths that the element absorbs when the full spectrum of light is shone through it. Every element has a unique absorption and emission spectrum.

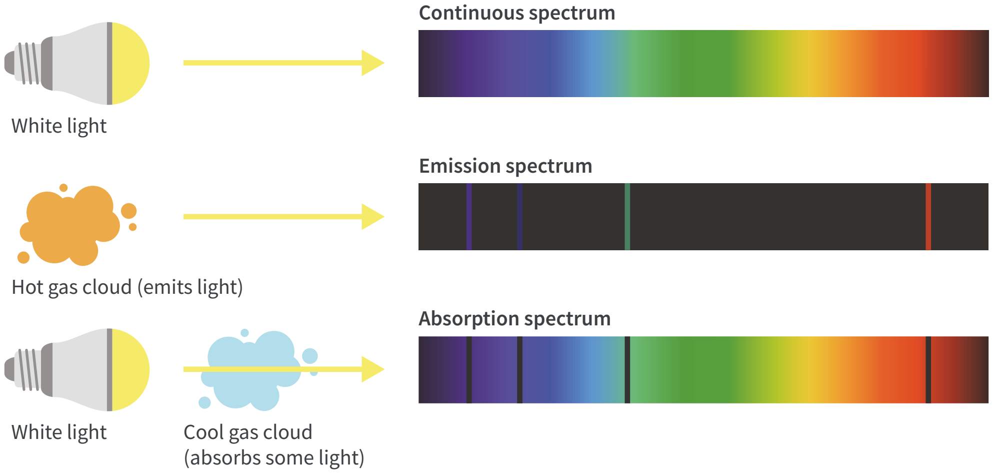


Figure 1 Light passing through a cold gas cloud produces an absorption spectra. A hot gas cloud of the same material produces spectral lines in matching locations.

Why do the emission and absorption spectra occur?

Electrons exist in an atom in quantised (or discrete) energy levels (see Figure 2). The energy level is commonly represented by the integer value $n = 1, 2, 3, \ldots$ The lowest energy level ($n = 1$) is known as the ground state. The electrons can transition between these energy levels by absorbing or emitting energy in the form of photons. Since energy is conserved, **the photon energy must equal the difference in energy levels**. An electron **must absorb a photon to transition to a higher energy level** and it must **emit a photon to transition to a lower energy level**. Since the electron energy levels are discrete, the photons also have discrete energies. This results in the observation of discrete spectral lines.

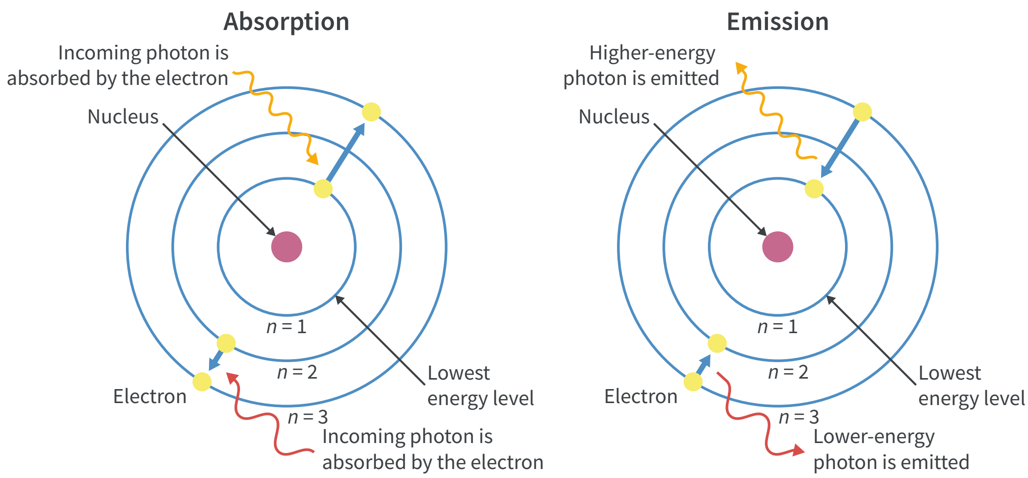


Figure 2 The increasing energy levels of an electron. Energy levels are represented by *n*.

$$E_{photon} = \Delta E$$

E_{photon} **= photon energy (eV or J),** ΔE **= change in energy level (eV or J)**

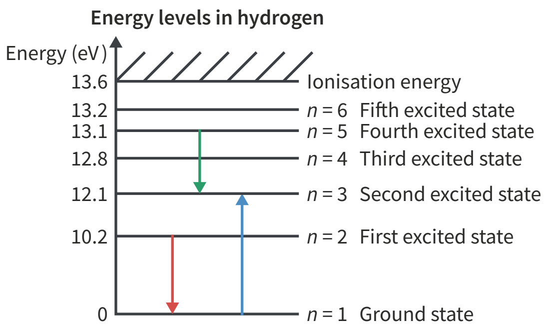


Figure 3 Electron energy levels in hydrogen. The arrows represent examples of electrons transitioning between energy levels.

An electron can transition between any two energy levels. We use an arrow to indicate this on an energy level diagram. Figure 3 shows transitions in a hydrogen atom. The red arrow shows an energy transition from $n = 2$ to $n = 1$ by emitting a photon of 10.2 eV. The blue arrow shows an energy transition from $n = 1$ to $n = 3$ by absorbing a photon of 12.1 eV. The green arrow shows an energy transition from $n = 5$ to $n = 3$ by emitting a photon of 1.0 eV.

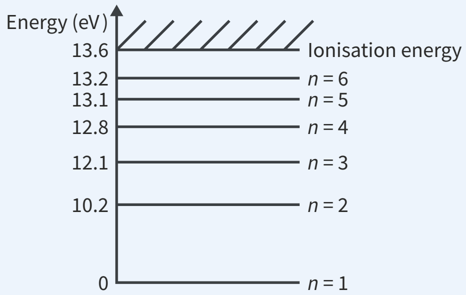
We use the phenomenon of electrons emitting photons as they change energy levels to light up our streets using metal vapour lamps. In a metal vapour lamp, a gaseous element is energised so that its electrons move into an excited state (higher energy level). They will then emit photons of discrete frequencies and wavelengths as the electrons transition to lower energy levels.

Ionisation

The ionisation energy represents the energy an electron needs to be emitted from the atom. Any incident photon greater than or equal to the ionisation energy of an electron will emit an electron from the atom. By the conservation of energy, $KE_{electron} = E_{photon} - E_{ionisation}$. In a metal, this ionisation energy is the same as the work function in the photoelectric effect.

1 **Worked example**

Energy levels in hydrogen



An electron in a hydrogen atom changes energy states from $n = 5$ to $n = 2$.

a **Will the electron emit or absorb a photon?**

b **What is the energy of the photon?**

a As an electron goes from $n = 5$ to $n = 2$, it is losing energy so it will emit that energy in the form of a photon.

b $E_{photon} = \Delta E = E_5 - E_2$

$E_5 = 13.1$ eV, $E_2 = 10.2$ eV

$E_{photon} = 13.1 - 10.2 = 2.9$ eV

Electron standing waves 4.2.11.1

OVERVIEW

Electrons can only exist if their orbital circumference forms a standing wave which means it must be an integer multiple of the de Broglie wavelength of the electron. This is further evidence that electrons exhibit wave-like properties.

THEORY DETAILS

An electron can exhibit both wave and particle properties, and the wave properties of an electron are used to explain why electrons exist only in discrete energy levels. An electron can exist only if its orbital circumference is an integer multiple of the electron's de Broglie wavelength (see Figure 4), allowing the electron to exist as a standing wave. This can also be written mathematically as $n\lambda = 2\pi r$, where $n = 1, 2, 3, ...$ This means that only discrete energies are allowed. If an electron were to orbit at a radius where it did not form a standing wave, the electron would destructively interfere with itself.

Note that, in this model, the electrons do not travel as particles along the path of a standing wave. Instead, each individual electron exhibits wave properties with a distributed location.

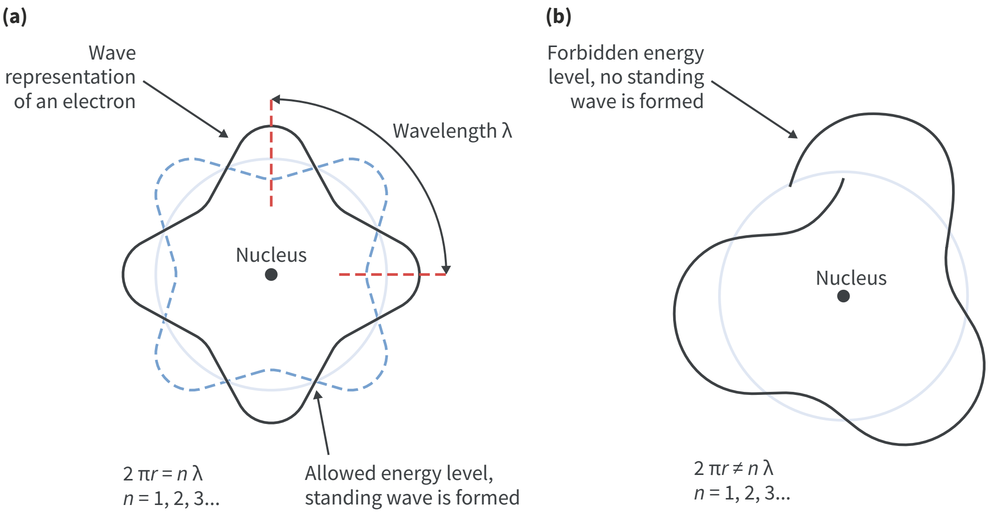


Figure 4 **(a)** An electron standing wave at the $n = 4$ energy level. **(b)** Circumferences that are not integer multiples of the de Broglie wavelength are not permitted.

USEFUL TIP

It is common to represent electrons forming standing waves using diagrams like Figure 4. To find the *n* value for an electron standing wave around a nucleus, count the number of wave peaks.

THEORY SUMMARY

- Electrons can only emit and absorb specific photon energies corresponding to the difference between energy levels.
  - $E_{photon} = \Delta E$
  - When a photon is absorbed, the electron transitions to a higher energy level.
  - When a photon is emitted, the electron transitions to a lower energy level.
- Metal vapour lamps use the emission spectra of an energised gas to produce light.
- Electrons can only exist in discrete energy levels where the circumference is an integer multiple of the electron's de Broglie wavelength. This forms a stable standing wave where constructive interference can occur.
- Discrete energy levels of electrons is evidence of their wave-like nature.

KEEN TO INVESTIGATE?

oPhysics 'Hydrogen Atom: Energy Levels' simulation

https://ophysics.com/m1.html

PhET 'Models of the Hydrogen Atom' simulation

https://phet.colorado.edu/en/simulation/legacy/hydrogen-atom

12C Questions

THEORY REVIEW QUESTIONS

Question 1

Why can an electron, in a given atom, emit photons with only certain energy values?

A Because total energy is conserved

B Because an electron can only exist in certain discrete energy levels

C Because an electron can transform its energy into the energy of a photon

D All of the above

Question 2

What physical phenomenon do metal vapour lamps utilise to produce light?

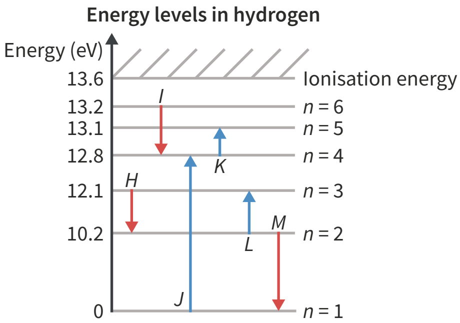
A Production of light in random thermal collisions

B Conversion of matter to pure energy

C Acceleration of electrons

D Change in electron energy levels of an energised gas

Use the following diagram to answer Questions 3–6.



Question 3

Which two electron transitions correspond to an emission and absorption of the same photon energy?

A *H*, *L* **B** *I*, *J* **C** *I*, *K* **D** *J*, *M*

Question 4

Which electron transition involves the absorption of the smallest wavelength of light?

A *I* **B** *J* **C** *K* **D** *M*

Question 5

Which of the following lists only transitions that are a result of an electron absorbing a photon?

A *J*, *M* **B** *H*, *I*, *M* **C** *J*, *K*, *H* **D** *J*, *K*, *L*

Question 6

Which of the following lists only transitions that are a result of an electron emitting a photon?

A *J*, *M* **B** *H*, *I*, *M* **C** *J*, *K*, *H* **D** *J*, *K*, *L*

Question 7

What happens if an electron absorbs a photon with a greater energy than its ionisation energy?

A The electron will spiral down into the nucleus.

B This is impossible, the electron will not absorb a photon greater than its ionisation energy.

C The electron will be ejected from the atom.

D The electron will go to a higher energy level.

Question 8

Why must electrons only exist in discrete energy levels?

A An electron is a particle, meaning that all its quantities, including orbit, must be discrete.

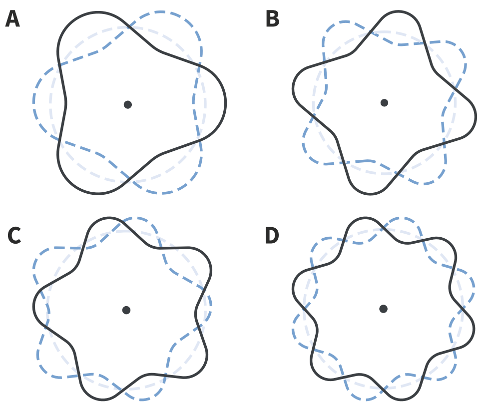
B An electron has wavelike properties and is stable only when a standing wave can form.

C An electron is a wave and waves are always discrete.

D This is not true. When an electron goes from one orbit to another it exists between discrete orbits.

Question 9

Which diagram represents the standing waves of an electron when $n = 3$?



EXAM-STYLE QUESTIONS

This lesson

Question 10 (3 MARKS)

Explain why a sodium vapour lamp emits discrete wavelengths of light.

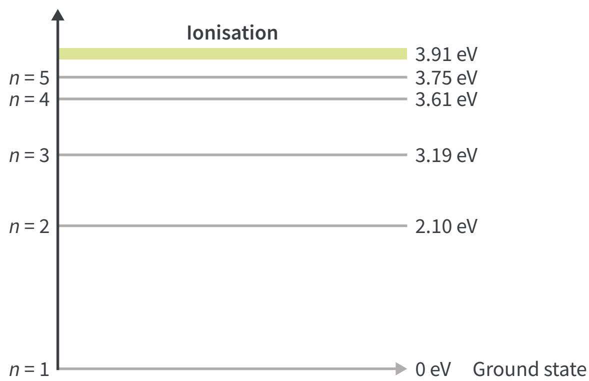
Adapted from 2018 VCAA Exam Section B Q19

Question 11 (4 MARKS)

How do wave-like properties of electrons explain discrete electron energy levels? Support your answer with a diagram.

Question 12 (10 MARKS)

Below is a diagram of the possible electron energy levels in a sodium atom.



a List all the different photon energies that the electron can emit as it returns to the ground state from the third excited state ($n = 4$). (3 MARKS)

Adapted from 2016 VCAA Exam Section A Q21c

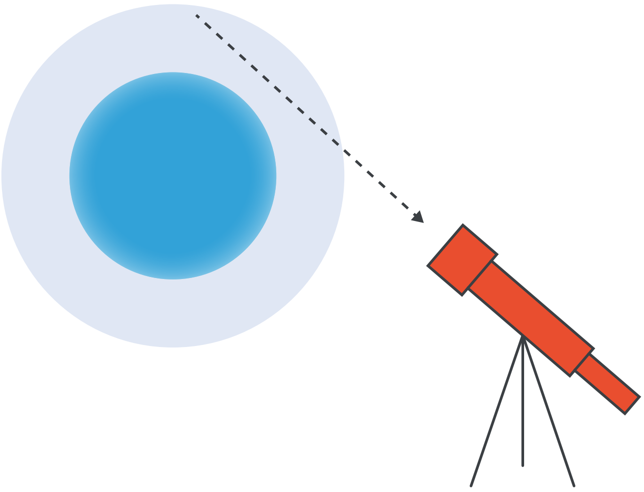
b Richard Feynman reports observing a photon of 2.3 eV emitted from the atom. Is this possible? Explain your answer. (2 MARKS)

c A sodium atom emits a photon of 1.353×10^{14} Hz. Draw an arrow to show the electron's change in energy levels. Support your drawing with a calculation. (2 MARKS)

d If a photon of 14 nm is absorbed by an electron in the ground state (n = 1), explain what would happen to the electron. Include the final electron energy in your answer. (3 MARKS)

Question 13 (2 MARKS)

Stephen Hawking wants to determine if there is mercury in the planet Mercury's exosphere by analysing the spectrum of light passing through it and reaching a telescope. Using your understanding of absorption spectra, explain how Stephen will be able to determine the presence of mercury in this exosphere.



Previous lessons

Question 14 (5 MARKS)

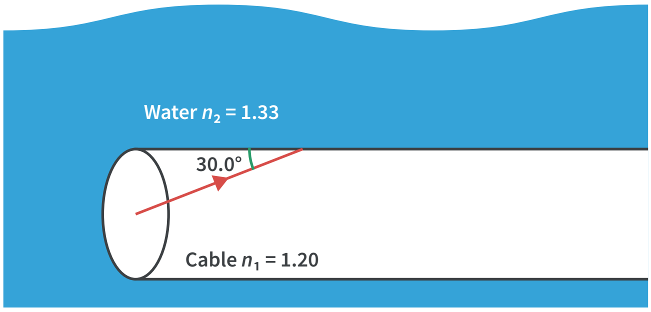
NASA's Juno space probe has a mass of 1590 kg and has been sent to Jupiter which has a mass of 1.90×10^{27} kg. Juno orbits Jupiter in an elliptical orbit. At its closest point, Juno is only 75 600 km from Jupiter's core, but at its furthest from Jupiter the space probe moves to 8.10×10^9 m from the planet's centre.

a Calculate the gravitational force that Juno experiences when it is furthest away from Jupiter. (2 MARKS)

b What is Juno's speed when it is closest to Jupiter? The orbit can be treated as circular at this point. (3 MARKS)

Question 15 (4 MARKS)

A ray of light enters a fibre-optic cable submerged in water.



a For the ray of light in the diagram, explain why or why not total internal reflection would occur? (2 MARKS)

b For the same ray of light, what is the maximum value of n_2 for which total internal reflection can occur in this cable? Give your answer to three significant figures. (2 MARKS)

Key science skills

Question 16 (4 MARKS)

Jane and Al are independently measuring wavelengths from the emission spectra of hydrogen.

Jane's measurements of a particular spectral line are: 124 nm, 120 nm, 127 nm (average 124 nm). Al's measurements of the same spectral line are: 116 nm, 130 nm, 117 nm (average 121 nm). The emission line is known to be at 122 nm.

a Comment on whose results were more precise. Justify your answer. (2 MARKS)

b Comment on whose results were more accurate. Justify your answer. (2 MARKS)

PRODUCTION OF LIGHT

In this lesson we will learn and compare how LEDs, lasers, incandescent globes, and synchrotrons produce light.

12A Comparing light and matter	12B Heisenberg's uncertainty principle	12C Absorption and emission spectra	12D Production of light

Study design key knowledge dot point

- compare the production of light in lasers, synchrotrons, LEDs and incandescent lights

Key knowledge units

Comparison of light sources	4.2.15.1

No previous or new formulas for this lesson

Definitions for this lesson

coherent light a beam of light with a consistent frequency and phase

monochromatic light light of a single frequency

Comparison of light sources 4.2.15.1

OVERVIEW

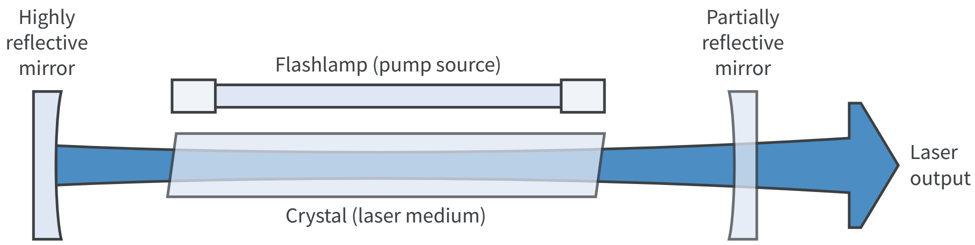
Light is produced when charged particles accelerate or when electrons transition from a higher to a lower energy state. This lesson will compare common technologies we use to produce light.

THEORY DETAILS

Laser

The word laser is an acronym for '**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation'. Inside a laser, atoms are energised by a pump source which excites their electrons. When the excited electrons return to their ground state they emit a photon of a single frequency. These monochromatic photons bounce between two mirrors, and stimulate the other atoms in the laser to release more of the same photons which amplifies the light (makes it more intense). Eventually, the light escapes through the one partially reflective mirror, as shown in the diagram.

A laser produces light which is coherent, high intensity, monochromatic (single frequency), and directional. Due to these properties, laser light stays focused over long distances.



The synchrotron utilises these principles to generate light when the electrons are forced to change direction by the magnetic fields. The light is emitted with extreme intensity in a direction which is tangential to the electron path. Synchrotrons can emit a broad range of electromagnetic frequencies (but specific frequencies can be tuned) in highly polarised beams.

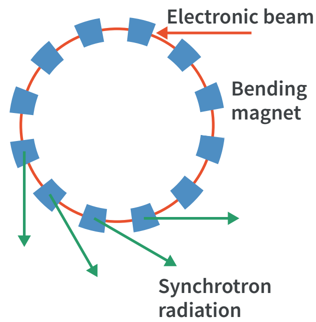


Figure 2 The red circle shows the path of electrons as they are accelerated by extremely strong magnets (the blue boxes) in a synchrotron. The green arrows represent the resultant light.

LED (light-emitting diode)

A diode has a specific energy gap between particular electron energy levels. When electrons transition from a higher energy level known as the conduction band to a lower energy level known as the valence band, they release a photon with energy equivalent to the change in electron energy. This occurs when electrons move across the junction of an N-type semiconductor (material with an excess of electrons) to a P-type semiconductor (material with a lack of electrons) within the diode. A current replenishes the electrons in the N-type semiconductor and removes the extra electrons from the P-type semiconductors.

The intensity of light emitted depends on the input current and can be easily controlled. LEDs are very energy efficient (they generate much less heat than incandescent lights), typically cheap, long lasting, and emit a very narrow (but not quite monochromatic) spectrum of light (see Figure 5). Uniquely, they can be switched on and off very quickly (in a nanosecond) which helps improve efficiency.

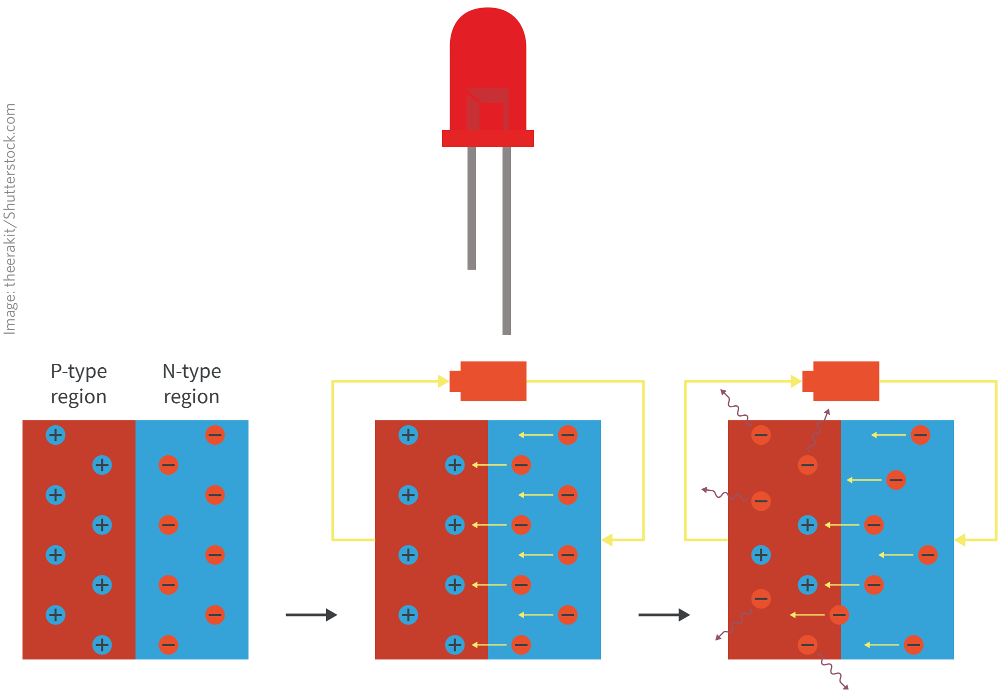


Figure 3 Electrons move from the N-type to the P-type semiconductors, changing the energy level of the electrons and emitting light in the process.

Incandescent globe

Incandescent bulbs produce light through the acceleration of electrons in random thermal collisions. This is called black body radiation. In an incandescent bulb, an electric current passes through a thin filament (often made of tungsten) until it is hot enough that the thermal collisions create visible light. Incandescent lighting is inefficient (usually less than 20% efficient), low intensity, and produces a wide range of electromagnetic radiation (see Figure 5).

Figure 4 The heated tungsten filament of an incandescent globe

Comparison of the spectrum produced by different light sources

Figure 5 shows a comparison of the emission spectrum of LEDs, lasers, incandescent globes, and synchrotrons. Observe that both lasers and LEDs produce thin spikes in their spectra. Synchrotrons and incandescent lights produce radiation across a broad spectrum. The spectrum of an incandescent bulb's light is most intense around the infrared end of the spectrum, which is why it is very inefficient. In comparison, a synchrotron's light is most intense around x-rays.

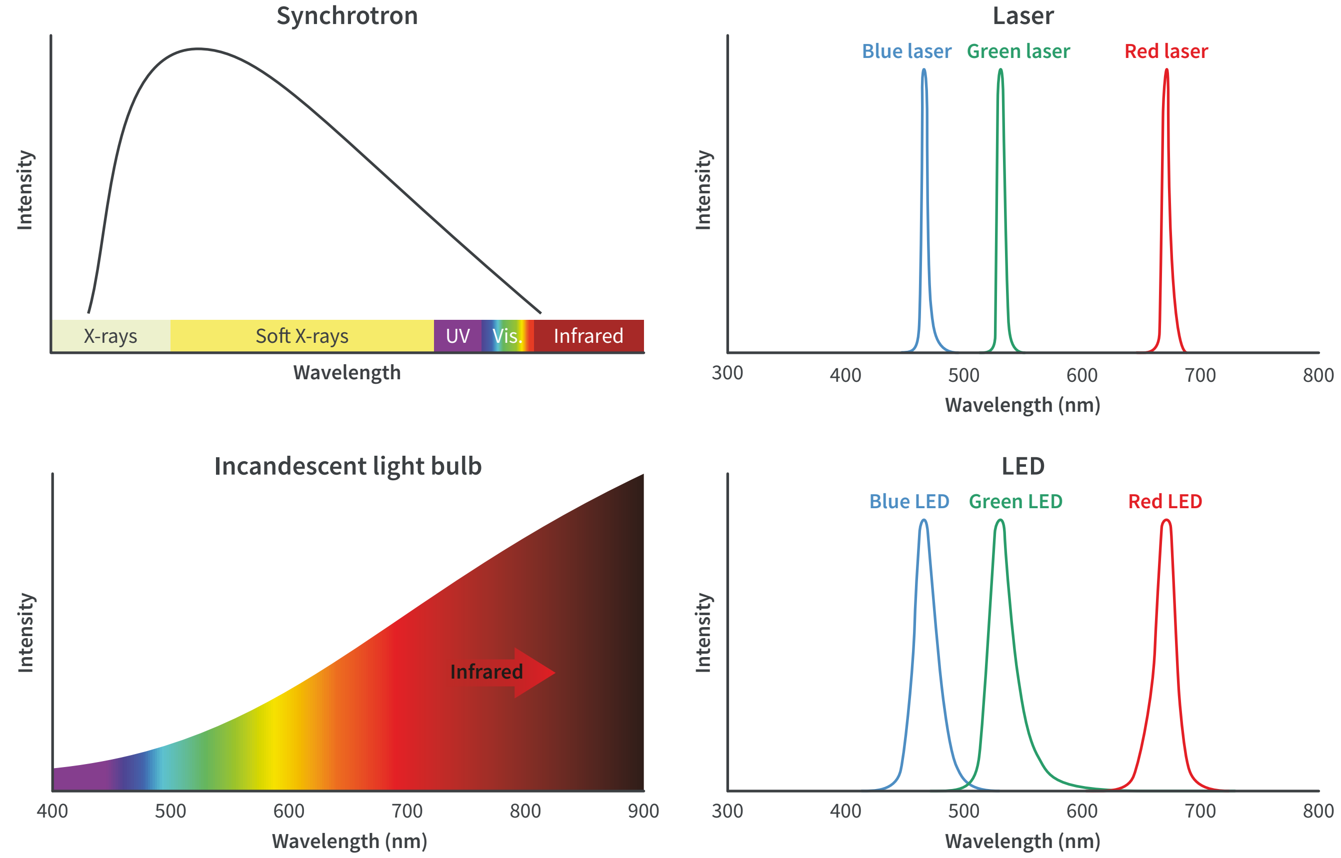


Figure 5 The spectra produced by lasers, synchrotrons, LEDs, and incandescent lights

Theory summary

Comparison of light sources

	Cause of light production	Features of the light
Laser	Electron transitions in atoms in a gas due to stimulated emission	Coherent, polarised
Synchrotron	Acceleration (deflection) of charged particles (electrons) due to magnetic fields	Wide range of wavelengths, polarised, very intense (can be coherent)
LED	Electron transition in semiconducting material from conduction band to valence band	Can be monochromatic (single wavelength)
Incandescent	Acceleration of charged particles due to thermal vibrations	Continuous spectrum

KEEN TO INVESTIGATE?

ANSTO 'The Austalian Synchrotron'
https://www.ansto.gov.au/research/facilities/australian-synchrotron/overview

Hyperphysics 'Lasers'
http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/qualig.html#c2

YouTube video: Minutephysics – How lasers work (in theory)
https://youtu.be/y3SBSbsdiYg

YouTube video: Minutephysics – How modern light bulbs work
https://youtu.be/oCEKMEeZXug

12D Questions

THEORY REVIEW QUESTIONS

Question 1

Which of the following best describes how light can be produced?

A Electrons accelerate or move from a higher to a lower energy state.

B An electron moves from a lower to higher energy state.

C Neutrons accelerate from rest.

D Electrons move close to the speed of light or move from a lower to a higher energy state.

Question 2

Which light source always produces coherent light?

A Laser

B Synchrotron

C LED

D Incandescent

Question 3

Which light sources produce light due to a change in electron energy levels?

A Lasers and incandescent lights

B Synchrotrons and LEDs

C LEDs and lasers

D Incandescent lights and synchrotrons

Question 4

Which light sources produce light from the acceleration of charged particles?

A Lasers and incandescent lights

B Synchrotrons and LEDs

C LEDs and lasers

D Incandescent lights and synchrotrons

EXAM-STYLE QUESTIONS

This lesson

Question 5 (1 MARK)

An electron is accelerated around a circular path in a __________. This produces _________ in a direction ______ to the direction of motion.

A	Laser	Electromagnetic radiation	Perpendicular
B	Synchrotron	Electromagnetic radiation	Tangential
C	Laser	Photons	Tangential
D	Synchrotron	Photons	Perpendicular

Question 6 (1 MARK)

The production of light by an LED can best be described by

A electrons transitioning from a high to a low energy state, releasing the difference in energy as electromagnetic radiation.

B accelerating a particle around a circular track.

C the black body radiation of a hot metal.

D heating of a gas to excite its electrons, which then drop energy levels, producing light.

Question 7 (1 MARK)

The Boltzmann family are thinking of buying a new lighting system for their home and can choose either LEDs or incandescent globes. LEDs are often considered a superior choice because

A LEDs produce a broader range of wavelengths.

B LEDs produce more thermal energy, helping to heat up the house during winter.

C LEDs are an older and therefore far more reliable lighting source.

D LEDs are far more efficient than incandescent bulbs, helping them save on electricity costs.

Question 8 (1 MARK)

Which of the following best describes the light emitted by a laser?

A Coherent light of a single wavelength

B Incoherent light with a single wavelength

C Coherent light with a broad range of wavelengths

D Incoherent light with a broad range of wavelengths

Question 9 (1 MARK)

Which best describes how an incandescent bulb produces light?

A Heating of a gas to excite its electrons, which then drop energy levels, producing light

B Accelerating electrons in random thermal collisions

C Accelerating electrons around a circular path

D Electrons moving from an N-type to P-type semiconductor

Previous lessons

Question 10 (5 MARKS)

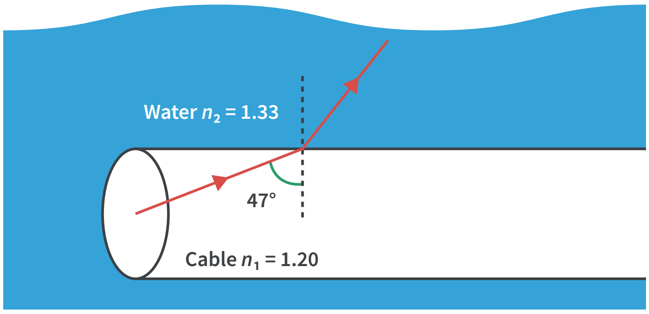
Elon Musk has recently launched a new constellation of satellites. In order to decrease internet latency he places them in orbit 540 km above the Earth's surface. Earth's mass is 5.98×10^{24} kg, Earth's radius is 6.37×10^{6} m, and the gravitational constant G is 6.67×10^{-11} N m^{2} kg^{-2}.

a What is the orbital period of Elon Musk's satellites? (3 MARKS)

b What is the speed of his satellites? (2 MARKS)

Question 11 (2 MARKS)

The diagram below shows light in a cable that is submerged in water.



With respect to the normal, at what angle would the light refract when leaving the cable?

Key science skills

Question 12 (2 MARKS)

Marie Curie uses a photometer to determine the intensity of her light source in lux. The image shows a reading of 2253 lux.

Image: Egoreichenkov Evgenii/Shutterstock.com

a How would the uncertainty in a measuring device like the photometer shown be found? (1 MARK)

b Hence calculate the uncertainty in the measurements for the device shown. (1 MARK)

CHAPTER 12 QUESTIONS

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

How can Heisenberg's uncertainty principle be used to explain the diffraction of an electron through a single slit?

A When moving through a slit the uncertainty in an electron's position decreases, which increases the uncertainty in the direction in which the electron is travelling.

B When moving through a slit the uncertainty in an electron's momentum increases, which increases the uncertainty in the electron's position.

C When moving through a slit the uncertainty in an electron's position decreases, which decreases the uncertainty in the direction in which the electron is travelling.

D Diffraction cannot be explained by Heisenberg's principle. It can only be explained by the de Broglie wavelength of the electron.

Question 2

Spectral lines in the emission and absorption spectra of an atom can be best explained by

A electrons behaving as discrete particles.

B electrons having the same energy as the photons corresponding to the spectral lines.

C electrons having the same wavelength as the photons corresponding to the spectral lines.

D electrons behaving as waves, only allowing them to form standing waves around a nucleus.

Adapted from 2017 VCAA Exam Section A Q17

Question 3

Which best gives the properties of laser light?

	Coherence	Spectrum	Intensity
A	Coherent	Single wavelength	High
B	Not coherent	Broad spectrum	Low
C	Not coherent	Monochromatic	High
D	Coherent	Narrow spectrum	Low

Question 4

An incandescent light bulb uses which principle to produce light?

A Electrons are accelerated around a circular track.

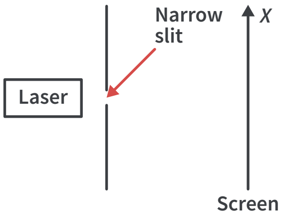
B A change in the energy levels of an electron.

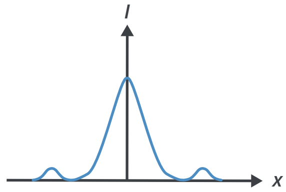
C The acceleration of electrons in random thermal collisions.

D A gas is heated up until it emits thermal radiation.

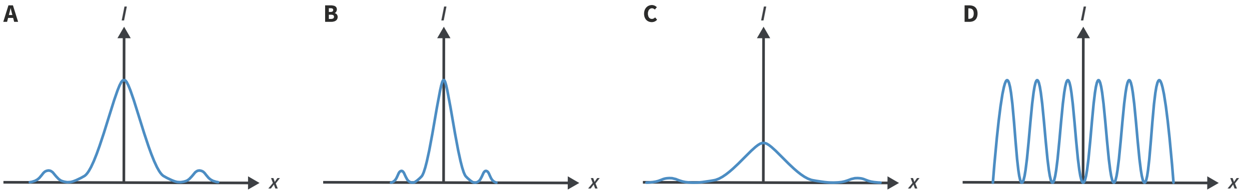
Question 5

Monochromatic laser light shines through a narrow slit, with the experimental setup shown below on the left. The intensity graph of the resulting pattern is shown below on the right.





Which one of the following intensity graphs best represents the pattern that would be seen if a slightly wider slit were used?



2019 VCAA NHT Exam Section A Q15

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)

Draw a diagram that shows the wave nature of an electron in an $n = 3$ orbit around the nucleus. (3 MARKS)

Question 7 (4 MARKS)

Harry Potter and Hermione Granger are having an argument.

Harry, ironically, doesn't believe in magic. He states that for an electron to get from one orbit to another it must increase or decrease its energy over time, meaning momentarily the electron must exist between energy levels. Hermione disagrees with Harry. She read that an electron will instantly jump between energy levels and she claims that this knowledge isn't even magic; it's physics!

Identify who is correct and justify your answer with reference to the wave nature of matter.

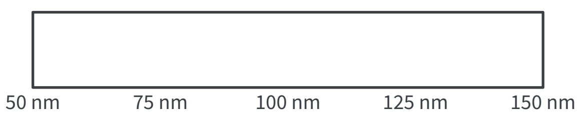
Question 8 (12 MARKS)

a Draw arrows on the energy level diagram to represent all the possible transitions for which an electron can emit a photon when transitioning from the $n = 5$ state. (2 MARKS)

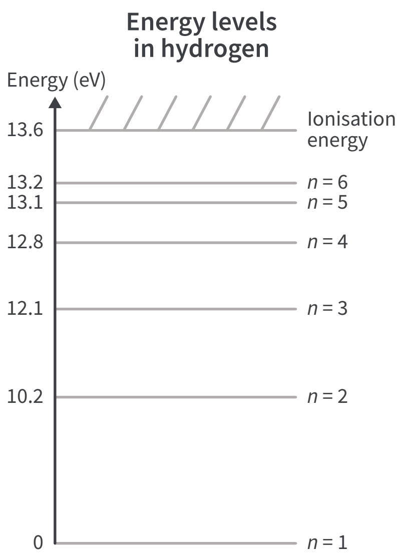
b What is the lowest frequency photon that can be emitted by a hydrogen atom in the $n = 5$ state? (2 MARKS)

c What is the longest wavelength photon that can be absorbed by a hydrogen atom in the $n = 3$ state? (2 MARKS)

d Copy the diagram and draw the spectral lines that would appear in the emission spectra of a hydrogen vapour lamp as an electron transitions from $n = 6$ to $n = 1$ and $n = 2$ to $n = 1$. Show your working. (3 MARKS)



e Identify the conditions for an electron to occupy a stable orbit with reference to the wave behaviour of electrons. (3 MARKS)



Question 9 (6 MARKS)

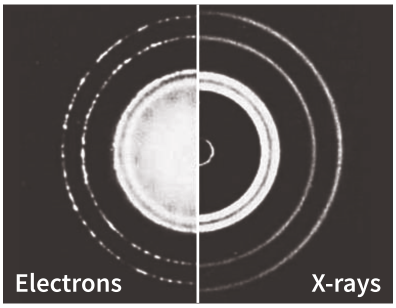
a Isabella is attempting to explain to Alessandro that you can not apply Heisenberg's uncertainty principle to heavy objects which is why we must apply the classical laws of physics to them. Allesandro counters explaining that heavy objects do follow Heisenberg's principle.

Evaluate the pair's statements. (3 MARKS)

b Explain how Heisenberg's uncertainty principle can be used to explain electron diffraction in the single slit experiment. (3 MARKS)

Question 10 (10 MARKS)

Scientists set up an experiment to compare electron and X-ray diffraction patterns. A laser was used to shoot 6.0×10^{16} Hz X-rays through a thin foil sheet, and afterwards they fired electrons using an electron gun though the same sheet. Both the electrons and X-rays produced diffraction patterns with the same spacing.



a What do their results reveal about the nature of matter? Justify your answer. (2 MARKS)

b What is the de Broglie wavelength of the electrons? Give your answer in nanometres. (3 MARKS)

c Calculate the momentum of the X-ray photons. (2 MARKS)

d Calculate the kinetic energy of the electrons in joules. (3 MARKS)

Adapted from 2018 VCAA Exam Section B Q18

Question 11 (3 MARKS)

Bonnie reads in an article that 'all electromagnetic radiation is produced by atomic energy level transitions'. Evaluate this statement with reference to light from lasers, incandescent globes, synchrotrons, and LEDs.

Adapted from 2019 VCAA NHT Exam Section A Q12

Question 12 (3 MARKS)

Describe how a sodium vapour lamp produces light.

Question 13 (4 MARKS)

The single photon double slit experiment is performed to display the wave-particle duality of light. Identify one result of the experiment which supports the particle model and a second result which does not. Explain why these results support or do not support the particle model of light.

UNIT 4, AOS 2 QUESTIONS

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 light-emitting diode produces visible light by

A accelerating electrons through thermal collisions.

B accelerating electrons using magnetic fields.

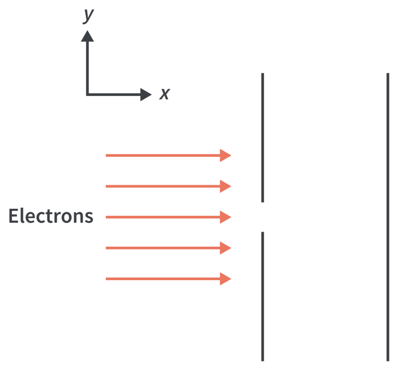
C passing light through a gaseous medium in order to stimulate atoms to produce coherent and monochromatic light.

D electrons changing energy levels when they transition to a lower energy state inside a semiconductor.

Question 2

Electrons travel towards a slit, as shown in the diagram, and a diffraction pattern is produced on the screen behind the slit.

Which of the following is the best explanation for the existence of the electron diffraction pattern on the screen behind the slits?



A A reduction in *x*-position uncertainty causes an increase in *x*-momentum uncertainty.

B A reduction in *y*-position uncertainty causes an increase in *y*-momentum uncertainty.

C A reduction in *y*-momentum uncertainty causes an increase in *y*-position uncertainty.

D As electrons are always particles, the diffraction pattern is a result of them bouncing off the walls of the slit.

Question 3

The wave model fails to make accurate predictions about the photoelectric effect. One of the predictions of the wave model is that any frequency of incident light could produce a photocurrent. Which one of the following correct observations from the photoelectric experiment disproved this prediction?

A For a given frequency, increasing intensity does not affect the kinetic energy of photoelectrons.

B The maximum kinetic energy of photoelectrons depends upon the work function of the metal.

C At a certain frequency, increasing intensity increases maximum photocurrent.

D There exists a threshold frequency.

Question 4

A diffraction pattern is produced when electrons with a speed of 3.56×10^5 m s^{-1} pass through a single slit. In a second experiment with the same apparatus, the speed of the electrons is increased to 7.82×10^5 m s^{-1}. The resulting diffraction pattern will

A be the same.

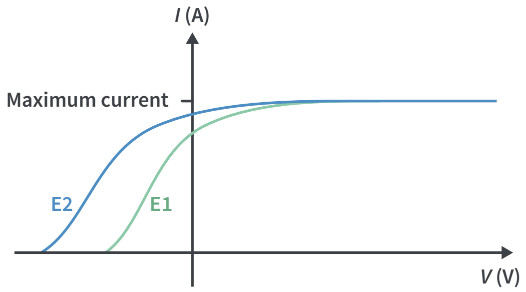
B have a larger spread.

C have a smaller spread.

D cease to exist.

Question 5

Two photoelectric effect experiments are conducted using incident light with the **same frequency**. The measured photocurrent is plotted against electrode potential for both experiments. Which of the following statements could provide a complete explanation for the different results observed between experiment one (E1) and experiment two (E2).



A The metal plate used in E1 has a greater threshold frequency than that used in E2.

B The light used in E1 has a higher intensity than in E2.

C The light used in E1 has a lower intensity than in E2.

D The metal plate used in E1 has a lower threshold frequency than that used in E2.

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)

An electron emerges from a particle accelerator with a kinetic energy of 1.3 eV. Ignore relativistic effects for this question.

a Calculate the de Broglie wavelength of the electron. (3 MARKS)

b Determine the momentum of a photon which would diffract by the same amount as an electron travelling at 7.92×10^6 m s^{-1} when diffracted through the same silicon lattice. (2 MARKS)

Question 7 (4 MARKS)

Explain two incorrect predictions that the wave model makes regarding the photoelectric effect and identify the results which disprove these predictions.

Question 8 (3 MARKS)

A group of students are performing the photoelectric experiment with an unknown metal cathode. The table describes the work function of various possible metals.

Metal	Work function (eV)
Sodium	2.38
Calcium	2.98
Copper	4.70
Platinum	6.39

The students use a beam of photons with a frequency of 1.14×10^{15} Hz. Photocurrent is measured only when the reverse potential applied between the metal cathode and the collector plate is less than 1.72 V. Determine which metal is being used.

Question 9 (1 MARK)

When successive individual electrons are passed through a set of double slits, an interference pattern forms on the screen behind the slits. This observation supports the dual wave-particle model of electrons. Identify which feature of the results of the single electron double-slit experiment indicate particle behaviour.

Question 10 (9 MARKS)

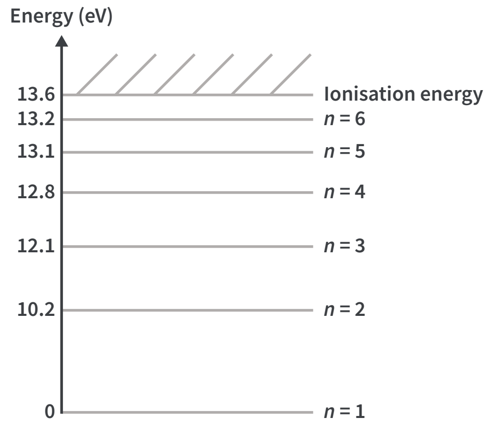
The diagram shows the electron energy levels of a hydrogen atom. Consider the photon emitted when an electron transitions from $n = 6$ to $n = 2$.

a Show that the energy of the photon is 4.8×10^{-19} J. (2 MARKS)

b Calculate the momentum of an **electron** that has a kinetic energy of 4.8×10^{-19} J. (2 MARKS)

c Identify all the possible energies (in eV) of the photons that could be emitted due to transitions when an electron starts in the $n = 5$ state and ends in the $n = 3$ state. (3 MARKS)

d Explain why electrons in atoms exist in discrete energy levels only. (2 MARKS)



Question 11 (2 MARKS)

Identify one similarity and one difference between the light that is produced by a synchrotron and the light that is produced by incandescent light globes.

Question 12 (2 MARKS)

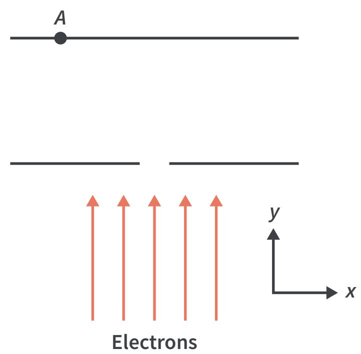
Tai is investigating the photoelectric effect using photons with a frequency of 9.82×10^{14} Hz incident on a plate of zinc. The work function of zinc is 4.33 eV. Will a photoelectron be released in this experiment?

Question 13 (3 MARKS)

A single slit experiment using electrons is set up as shown.

Electrons are passing through the slit but the diffraction pattern does not spread as wide as point *A*.

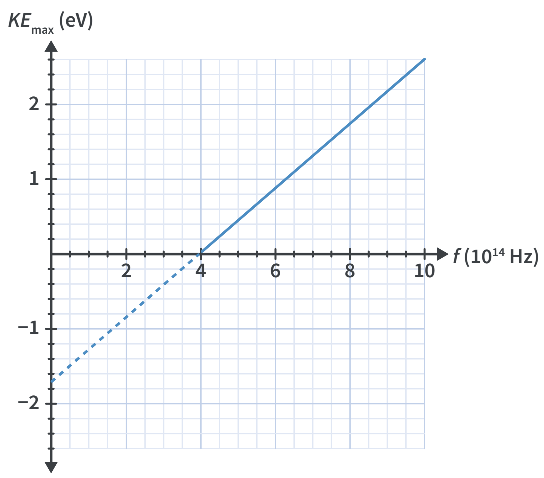
Explain how the speed of the electrons travelling through the slit could be changed so that the diffraction pattern spreads to point *A*.



Question 14 (3 MARKS)

The following graph is produced during a photoelectric effect experiment.

Use the graph to determine an experimental value for Planck's constant. Give your answer in J s.



Question 15 (3 MARKS)

Dorothy conducts two photoelectric effect experiments. She uses a different frequency of light for each experiment. In both cases, she starts with light that has a very low intensity and she measures the photocurrent as she steadily increases the intensity.

In the first experiment, she uses light with a fixed frequency of 6.0×10^{14} Hz and she finds that increasing the intensity causes an increase in the photocurrent. In the second experiment, she uses light with a fixed frequency of 2.0×10^{13} Hz and she finds that there is no current when the light intensity is low. This is summarised in the table.

	$f = 6.0 \times 10^{14}$ Hz	$f = 2.0 \times 10^{13}$ Hz
Low intensity	Low current	No current
High intensity	High current	?

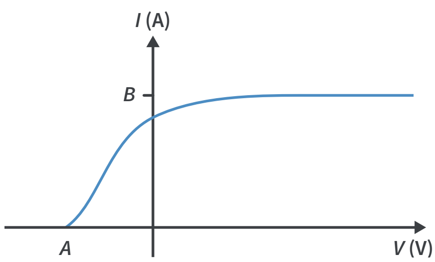
When she increases the intensity for the second experiment, she expects to measure a current.

Explain why she may believe this is the case, and whether her prediction is correct.

Adapted from 2018 VCAA Exam Section B Q17a

Question 16 (4 MARKS)

Bailey is investigating the effect of changing the frequency of light on photocurrent in the photoelectric experiment. The graph shows the photocurrent produced versus electrode potential for the first frequency used.



a Identify what values are represented by the *A* on the horizontal axis and the *B* on the vertical axis. (2 MARKS)

b Bailey repeats the experiment using light with double the frequency of the first experiment. Copy the graph and draw the expected results using a dotted line. (2 MARKS)

Question 17 (5 MARKS)

Calculate the energy of electrons that would produce the same diffraction pattern as X-rays with a frequency of 5.0×10^{18} Hz. Provide your answer in electron-volts.

Adapted from 2019 VCAA Exam Section B Q17b

1A Asking questions, identifying variables, and making predictions

Theory review questions

1 B

2 **a** Observation/measurement

b Model

c Theory

3 **a** DV **b** CV **c** IV

4 B and D

5 Quantitative: b, c, e.

Qualitative: a, d.

Exam-style questions

This lesson

6 **a** Mass of ball

b Time to reach the ground

c Height (1 MARK)

Initial speed (1 MARK)

d IV: height (1 MARK)

DV: speed just before hitting the ground (1 MARK)

CV: mass of ball used (1 MARK)

7 C

8 A

9 D

10 [If the final speed varies with the slope angle,[1]][then the final speed will increase when the slope angle increases.[2]]

- I have stated a predicted relationship between the DV (final speed) and the IV (slope angle).[1]
- I have explicitly addressed the effect on the DV (final speed) when the IV (slope angle) increases.[2]
- I have used an 'If...then...when...' statement.

1B Scientific conventions

Theory review questions

1 **a** 3 (trailing zeros are significant)

b 1

c 5 (all non-leading zeros are significant)

d 3

e 4 (leading zeros are not significant)

f 6

g 5 (leading zeros are not significant)

h 4 (leading zeros are not significant)

i 3

2 **a** 3.0×10^{3} (2 significant figures as per the accuracy mentioned in the question)

b 2.6×10^{6}

c 5.98×10^{4}

d 2.4×10^{-1} (note all digits beside leading zeros are significant)

e 4.5×10^{-4}

f 6.0×10^{-8}

3 **a** 45.6 (1 decimal place)

b 654.5 (1 decimal place)

c 49.281 (3 decimal places)

d 52 (0 decimal places)

e 60 (0 decimal places)

f 70.01 (2 decimal places)

4 **a** 28 (2 significant figures)

b 3.15×10^{-2} (3 significant figures)

c 1.2×10^{4} (2 significant figures)

d 1.7×10^{7} (2 significant figures)

e 3×10^{3} (1 significant figure)

f 2.33×10^{4} (3 significant figures)

5 **a** 3.2×10^{3} J

b 8.0×10^{-12} A

c $750 \text{ nm} = 750 \times 10^{-9} \text{ m} = 7.50 \times 10^{-7} \text{ m}$

d $500 \text{ ms} = 500 \times 10^{-3} \text{ s} = 5.00 \times 10^{-1} \text{ s}$

e $0.300 \text{ µg} = 0.300 \times 10^{-9} \text{ kg} = 3.00 \times 10^{-10} \text{ kg}$

f $54 \text{ MΩ} = 54 \times 10^{6} \text{ Ω} = 5.4 \times 10^{7} \text{ Ω}$

6 B, H, J, L

Exam-style questions

This lesson

7 **a** $F_{net} = ma = 0.250 \times 3.0$ (1 MARK)

$F_{net} = 0.75$ N (2 significant figures) (1 MARK)

b *total distance* = 132 + 56 = 188 m (3 significant figures) (1 MARK)

$speed = \dfrac{total\ distance}{time} = \dfrac{188}{22.0}$ (1 MARK)

$speed = \dfrac{188}{22.0} = 8.55 \text{ m s}^{-1}$ (3 significant figures) (1 MARK)

1C Collecting data

Theory review questions

1 a False b False c True d False
e False f True g True h True
i True j True k True l False
m True

Exam-style questions

This lesson

2 B 3 D 4 B 5 B
6 C 7 D 8 A 9 B
10 A 11 A 12 D 13 B

14 [Experimental uncertainty is the quantitative indicator of the random error associated with a measurement.[1]][One method to reduce experimental uncertainty is to use equipment that can take more precise measurements.[2]]

- I have explicitly addressed the meaning of experimental uncertainty.[1]
- I have explicitly addressed a way to reduce experimental uncertainty.[2]

15 [Multiple measurements can be averaged to find a value that is generally going to be more accurate than an individual measurement.[1]][This is because the variations of individual measurements from the 'true' value due to random errors will tend to offset each other when an average is taken.[2]]

- I have used the relevant theory: how averages affect accuracy.[1]
- I have used the relevant theory: reducing the effect of random error by taking an average.[2]

16 a Sam: $\frac{68 + 76 + 54 + 66}{4} = 66$ Hz (1 MARK)

Jess: $\frac{79 + 81 + 60 + 64}{4} = 71$ Hz (1 MARK)

b Sam: 76 − 54 = 22 Hz (1 MARK)

Jess: 81 − 60 = 21 Hz (1 MARK)

c [Sam's data is more accurate than Jess' data[1]][as Sam's average of 66 Hz is closer to the true frequency of 64 Hz than Jess' average of 71 Hz.[2]]

- I have explicitly compared the accuracy of Sam's and Jess' data.[1]
- I have used relevant theory: accuracy.[2]
- I have related my answer to the context of the question.

d [Jess' data is more precise than Sam's data[1]][as the range of Jess' results (21 Hz) is smaller than the range of Sam's results (22 Hz).[2]]

- I have explicitly compared the precision of Sam's and Jess' data.[1]
- I have used relevant theory: precision.[2]
- I have related my answer to the context of the question.

17 b, e, f, h, i (5 MARKS)

1D Representing and analysing data

Theory review questions

1 B. This is the only option for which the data takes up the majority of the graph space.

2 A line of best fit could be used for: b and d.
A curve of best fit must be used for: a, c, and e.

3 A

Exam-style questions

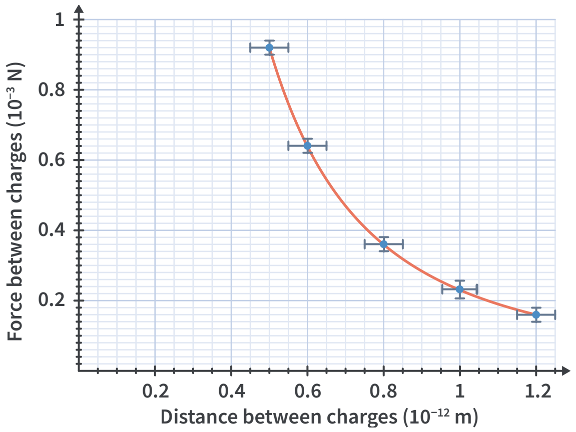
This lesson

4 a [Firstly, draw vertical uncertainty bars of equal size on each data point.[1]][Then test if a straight line can be drawn through the uncertainty bars of all data points. If it can, then a line of best fit is valid.[2]]

- I have used the relevant theory: uncertainty bars.[1]
- I have used the relevant theory: lines of best fit.[2]

b The graph can have a line of best fit

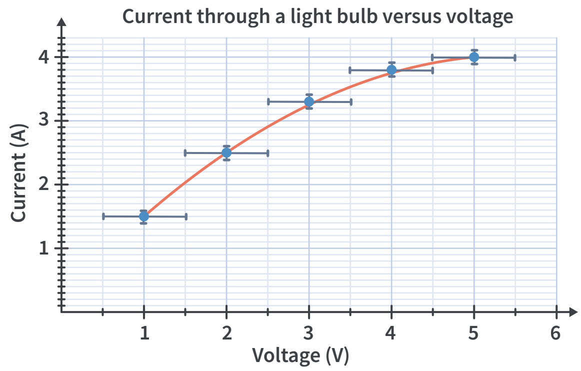
5



- 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: (0.50, 0.92), (0.60, 0.64), (0.80, 0.36), (1.00, 0.24), (1.20, 0.16)

- I have drawn correctly sized uncertainty bars: (horizontal: $\pm 0.05 \times 10^{-12}$ m, vertical: $\pm 0.02 \times 10^{-3}$ N)
- I have drawn a curve of best fit which passes through all uncertainty bars.

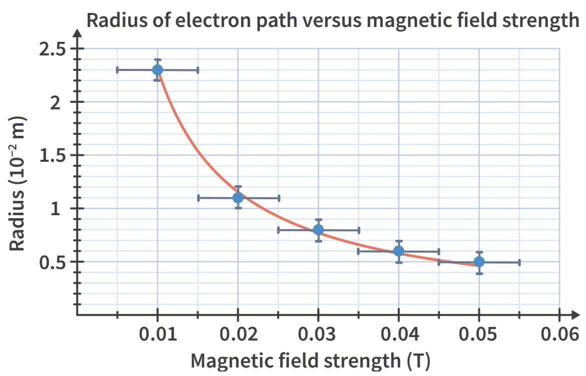
6 a



- 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: (1.0, 1.5), (2.0, 2.5), (3.0, 3.3), (4.0, 3.8), (5.0, 4.0)
- I have drawn correctly sized uncertainty bars: (horizontal: ± 0.5 V, vertical: ± 0.1 A)
- I have drawn a curve of best fit which passes through all uncertainty bars.

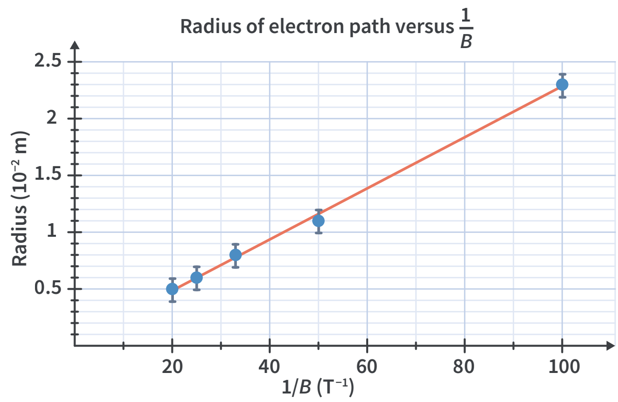
b The lightbulb is not an ohmic resistor (since a straight line does not fit the data).

7 a



- 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: (0.010, 2.3), (0.020, 1.1), (0.030, 0.8), (0.040, 0.6), (0.050, 0.5)
- I have drawn correctly sized uncertainty bars (horizontal: ± 0.005 T, vertical: $\pm 0.1 \times 10^{-2}$ m)
- I have drawn a curve of best fit which passes through all uncertainty bars.

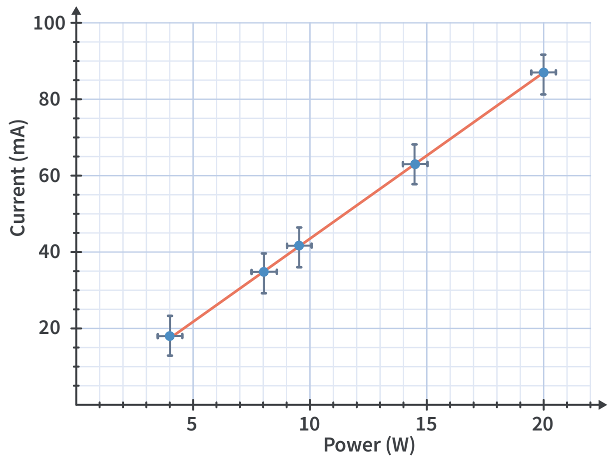
b



- 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: (20, 0.5), (25, 0.6), (33, 0.8), (50, 1.1), (100, 2.3)
- I have drawn correctly sized uncertainty bars: (vertical: $\pm 0.1 \times 10^{-2}$ m)
- I have drawn a line of best fit which passes through all uncertainty bars.

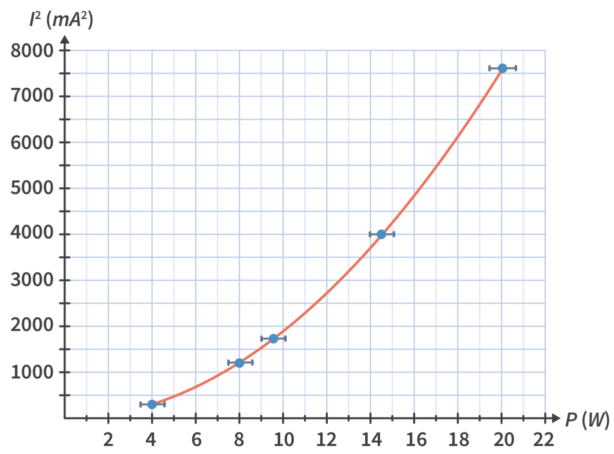
c Michael is correct that $r \propto \frac{1}{B}$ (since a straight line fits the linearised data).

8 a



- 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: (4.0, 18), (8.0, 35), (9.5, 42), (14.5, 63), (20.0, 87)
- I have drawn correctly sized uncertainty bars: (horizontal: ±0.5 W, vertical: ±5 mA)
- I have drawn a line of best fit which passes through all uncertainty bars.

b



- 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: (4.0, 324), (8.0, 1225), (9.5, 1764), (14.5, 3969), (20.0, 7569)
- I have drawn correctly sized uncertainty bars: (horizontal: ±0.5 W)
- I have drawn a curve of best fit which passes through all uncertainty bars.

c [Claire is not correct in saying that $P \propto I^2$[1]][as the graph in part **b** does not have a line of best fit.[2]][$P \propto I$ as the graph in part **a**[3]][has a line of best fit.[4]]

- I have explicitly answered the question.[1]
- I have used the provided data (the graph in part **b**) in my answer.[2]
- I have proposed the correct relationship using the provided data (the graph in part **a**) in my answer.[3]
- I have used the relevant theory: linearising data.[4]

1E Gradients of lines of best fit

Theory review questions

1 A **2** Q and S **3** B

Exam-style questions

This lesson

4 Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{75 - 10}{8.0 - 1.0} = 9.3 \text{ N kg}^{-1}$ (1 MARK)

$gradient = \frac{rise}{run} = \frac{F_g}{m} = g \therefore g = 9.3 \text{ N kg}^{-1}$ (1 MARK)

5 a Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{20 - 5}{4.0 - 1.0}$ (1 MARK)

$gradient = 5.0 \text{ N s}^2$ (1 MARK)

b $gradient = \frac{rise}{run} = \frac{F}{\left(\frac{1}{T^2}\right)} = FT^2$

The original equation is

$F = \frac{4\pi^2 mr}{T^2} \therefore FT^2 = 4\pi^2 mr \therefore gradient = 4\pi^2 mr$ (1 MARK)

$5.0 = 4 \times \pi^2 \times m \times 1.0$ (1 MARK)

$m = 0.13$ kg (1 MARK)

6 a Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{(25 - 9) \times 10^{-4}}{(3.9 - 1.4) \times 10^5}$ (1 MARK)

$gradient = 6.4 \times 10^{-9}$ s (1 MARK)

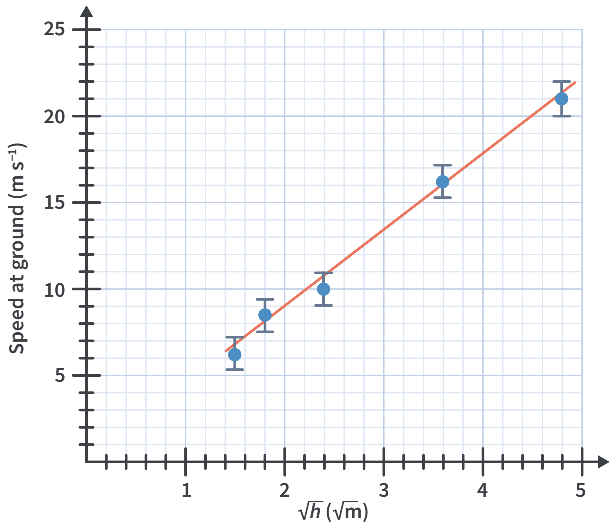
b $gradient = \frac{rise}{run} = \frac{r}{v}$

The original equation is $r = \frac{mv}{qB} \therefore \frac{r}{v} = \frac{m}{qB} \therefore gradient = \frac{m}{qB}$ (1 MARK)

$6.4 \times 10^{-9} = \frac{m}{1.6 \times 10^{-19} \times 8.7 \times 10^{-4}}$ (1 MARK)

$m = 8.9 \times 10^{-31}$ kg (1 MARK)

7 a



I have drawn a line of best fit that passes through all uncertainty bars.

I have drawn a line that passes through only the range of values for which we have data.

b Use any two points from the line of best fit that are far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{20-9}{4.5-2.0}$ (1 MARK)

$gradient = 4.4\ \sqrt{m}\ s^{-1}$ (1 MARK)

Gradient represents $gradient = \frac{rise}{run} = \frac{v}{\sqrt{h}}$

The original equation is

$v = \sqrt{2gh}\ \therefore \frac{v}{\sqrt{h}} = \sqrt{2g}\ \therefore gradient = \sqrt{2g}$ (1 MARK)

$4.4 = \sqrt{2g}$

$g = 9.7\ m\ s^{-2}$ (1 MARK)

Chapter 1 Review

Section A

1	D	**2**	B	**3**	D	**4**	B	**5**	B
6	C	**7**	C	**8**	C	**9**	B	**10**	C
11	B	**12**	C	**13**	A	**14**	B	**15**	A
16	B	**17**	B						

Section B

18 a i Independent: time

ii Dependent: speed

iii Controlled: mass of ball **OR** ramp height/length/angle **OR** ball type

b Identify two points on the line of best fit such as (0, 0) and (2.0, 1.5). (1 MARK)

$a = \frac{\Delta v}{\Delta t} = \frac{1.5-0}{2.0-0} = 0.75\ m\ s^{-2}$ (1 MARK)

19 a

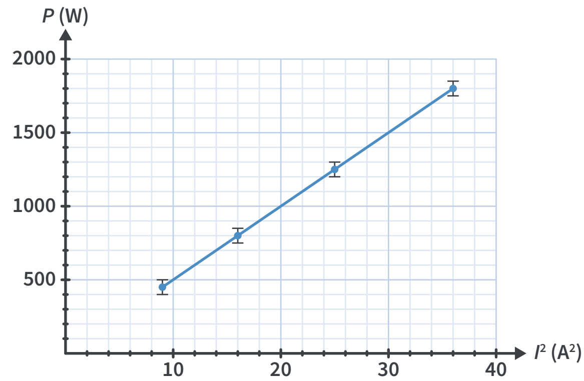
I^2 (A^2)
9.0
16
25
36

(1 MARK FOR CORRECT SIGNIFICANT FIGURES)

(1 MARK FOR CORRECT VALUES)

b Independent variable

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 axes.

I have plotted each point of data: (9, 450), (16, 800), (25, 1250), (36, 1800).

I have drawn correctly sized uncertainty bars.

I have drawn a straight line of best fit which passes through all uncertainty bars.

d $P = I^2 R\ \therefore gradient = R$ (1 MARK)

Identify two points on the line of best fit such as (34, 1700) and (10, 500).

$Gradient = \frac{rise}{run} = \frac{1700-500}{34-10}$ (1 MARK)

$R = 50\ \Omega$ (1 MARK)

20 a 6.54×10^{-3} m (2 MARKS)

b Independent: Separation of the charged bodies (1 MARK)

Dependent: Force between the charged bodies (1 MARK)

Controlled: Charge on the two spheres (1 MARK)

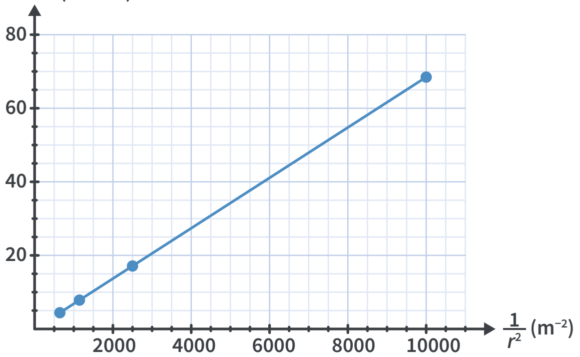
c

$\frac{1}{r^2}$ (m^{-2})
1.00×10^4
2.50×10^3
1.11×10^3
6.25×10^2

(1 MARK FOR CORRECT SIGNIFICANT FIGURES)

(1 MARK FOR CORRECT VALUES)

d



- 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 axes.
- I have plotted each point of data: (6.25×10^2, 4.31×10^{-28}), (1.11×10^3, 7.67×10^{-28}), (2.50×10^3, 1.73×10^{-27}), (1.00×10^4, 6.90×10^{-27}).
- I have drawn a straight line of best fit.

e $F = kq_1q_2 \times \frac{1}{r^2}$ $\therefore$ *gradient* $= kq_1q_2$ (1 MARK)

Identify two points on the line of best fit such as (1.00×10^4, 69.0×10^{-28}) and (625, 4.31×10^{-28})

$Gradient = \frac{rise}{run} = \frac{(69.0 - 4.31) \times 10^{-28}}{1.00 \times 10^4 - 625} = 6.90 \times 10^{-31}$ N m^2 (1 MARK)

$\therefore 6.90 \times 10^{-31} = k \times 5.00 \times 10^{-20} \times 1.50 \times 10^{-21}$ (1 MARK)

$k = 9.20 \times 10^9$ N m^2 C^{-2} (1 MARK)

2A Kinematics recap

Theory review questions

1 B **2** D **3** B **4** D **5** A

Exam-style questions

This lesson

6 $v = \frac{\Delta s}{\Delta t} = \frac{50}{20} = 2.5 \text{ m s}^{-1}$

7 $u = 0 \text{ m s}^{-1}, v = \frac{36}{3.6} = 10 \text{ m s}^{-1}$ (1 MARK)

$a = \frac{\Delta v}{\Delta t} = \frac{10 - 0}{2.0 - 0} = 5.0 \text{ m s}^{-2}$ (1 MARK)

8 $s = vt - \frac{1}{2}at^2 = 2.0 \times 6.0 - \frac{1}{2} \times 0.30 \times 6.0^2 = 6.6 \text{ m}$

9 $v^2 = u^2 + 2as = 4.0^2 + 2 \times 0.50 \times 30$ (1 MARK)

$v = 6.8 \text{ m s}^{-1}$ (1 MARK)

10 $s = \frac{1}{2}(v + u)t \ \therefore 30 = \frac{1}{2}(17 + 3.0)t$ (1 MARK)

$t = 3.0 \text{ s}$ (1 MARK)

11 $v = \frac{60}{3.6} = 16.7 \text{ m s}^{-1}$ (1 MARK)

$s = \frac{1}{2}(v + u)t \ \therefore 50 = \frac{1}{2}(16.7 + u) \times 3.6$ (1 MARK)

$u = 11.1 \text{ m s}^{-1} = 40 \text{ km h}^{-1}$ (1 MARK)

12 **a** $s = ut + \frac{1}{2}at^2 = 0 \times 4.0 + \frac{1}{2} \times 3.0 \times 4.0^2 = 24 \text{ m}$

b $v = u + at = 0 + 3.0 \times 4.0 = 12 \text{ m s}^{-1}$

13 Bill travels further. (1 MARK)

Yasmin: $v^2 = u^2 + 2as \ \therefore 0^2 = 1.70^2 + 2 \times (-0.500) \times s$ (1 MARK)

$s = 2.89 \text{ m}$ (1 MARK)

Bill: $v^2 = u^2 + 2as \ \therefore 0^2 = 1.60^2 + 2 \times (-0.400) \times s$ (1 MARK)

$s = 3.20 \text{ m}$ (1 MARK)

14 Define upwards as positive.

$s = 15 \times 0.30 = 4.5 \text{ m}$ (1 MARK)

$s = vt - \frac{1}{2}at^2 \ \therefore 4.5 = 0 \times 10 - \frac{1}{2} \times a \times 10^2$ (1 MARK)

$a = -0.090 \text{ m s}^{-2}$ (1 MARK)

15 Graham ends up running at a faster pace. (1 MARK)

Ryan: $v^2 = u^2 + 2as \ \therefore v^2 = 1.0^2 + 2 \times 0.30 \times 10$ (1 MARK)

$v = 2.6 \text{ m s}^{-1}$ (1 MARK)

Graham: $v = u + at = 0.80 + 0.40 \times 5.0 = 2.8 \text{ m s}^{-1}$ (1 MARK)

16 $s = ut + \frac{1}{2}at^2 = 1.5 \times 2.0 + \frac{1}{2} \times 2.0 \times 2.0^2 = 7 \text{ m}$ (1 MARK)

$7 < 10$, so the shark will not catch the fish. (1 MARK)

OR

$s = ut + \frac{1}{2}at^2 \ \therefore 10 = 1.5 \times t + \frac{1}{2} \times 2.0 \times t^2 \ \therefore t = 2.5 \text{ s}$ (1 MARK)

$2.5 > 2$, so the shark will not catch the fish. (1 MARK)

17 **a** $v = \frac{\Delta s}{\Delta t} \ \therefore 2.5 = \frac{600}{\Delta t}$ (1 MARK)

$\Delta t = 240 \text{ s}$ (1 MARK)

b $v^2 = u^2 + 2as \ \therefore v^2 = 2.5^2 + 2 \times (-0.1) \times 20$ (1 MARK)

$v = 1.5 \text{ m s}^{-1}$ (1 MARK)

$s = \frac{1}{2}(v + u)t \ \therefore 20 = \frac{1}{2} \times (1.5 + 2.5) \times t$ (1 MARK)

$t = 10 \text{ s}$ (1 MARK)

c $v^2 = u^2 + 2as \ \therefore v^2 = 1.5^2 + 2 \times 0.60 \times 20$ (1 MARK)

$v = 5.1 \text{ m s}^{-1}$ (1 MARK)

$s = \frac{1}{2}(v + u)t \ \therefore 20 = \frac{1}{2} \times (5.1 + 1.5) \times t$ (1 MARK)

$t = 6.0 \text{ s}$ (1 MARK)

d $t = 240 + 10 + 6 = 256 \text{ s}$

Key science skills

18 **a** Using any two points from the line such as (10,8) and (2,4),
$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{8 - 4}{10 - 2}$ (1 MARK)

$gradient = \frac{4}{8} = 0.5 \text{ m s}^{-1}$ (1 MARK)

b [A gradient is a rate that indicates the change in the vertical axis per unit of the horizontal axis.[1]][In this case, that is the displacement per second. This is the rate of change of displacement with respect to time, which is the definition of velocity.[2]]

I have used the relevant theory: gradients.[1]

I have used the relevant theory: velocity.[2]

c $v = 0.5 \text{ m s}^{-1}$ to the south (2 MARKS)

2B Forces recap

Theory review questions

1 B **2** A **3** B **4** D

5 D **6** A

Exam-style questions

This lesson

7 Taking right as the positive direction: $6 + 3 + (-4) = 5 \text{ N}$

Sum: $\xrightarrow{\textbf{5 N}}$

I have drawn a vector in the direction defined as positive.

I have labelled the magnitude of the vector.

8 $a = \frac{F_{net}}{m} = \frac{70}{30} = 2.3 \text{ m s}^{-2}$

9 $F_{net} = ma = 2000 \times 30 = 6.0 \times 10^4 \text{ N}$

10 [When the rocket expels the gases it exerts a force on them. As described by Newton's 3rd law, this force will have an equal and opposite reaction force.[1]][In this case, the gases exert a force on the rocket in the opposite direction, accelerating the rocket.[2]]

I have used the relevant theory: Newton's third law.[1]

I have explicitly addressed how the expelled gases accelerate the rocket.[2]

11 Assuming up and to the right as positive:

Vector A: $A_x = -50 \times \cos(35°) = -41$ N (1 MARK)

$A_y = 50 \times \sin(35°) = 29$ N (1 MARK)

Vector B: $B_x = 60 \times \cos(65°) = 25$ N (1 MARK)

$B_y = 60 \times \sin(65°) = 54$ N (1 MARK)

12 [The three forces acting on the ball cannot hold it stationary,[1]] [because the upward component of F_C cannot be balanced out by a force in the opposite direction. For the ball to be held stationary, the net force must be zero.[2]]

I have explicitly addressed if the ball can be held stationary.[1]

I have used the relevant theory: net force.[2]

13 **a** $F_g = mg = 1000 \times -9.8 = -9.8 \times 10^3$ N

b Since the boat is not accelerating in the vertical direction:
$F_N = -F_g = 9.8 \times 10^3$ N

c [The boat exerts a contact force on the ground as a result of the gravitational force on the boat. From Newton's 3rd law, we know that as a result of this contact force,[1]] [a reaction force is exerted on the boat by the ground, known as the normal force.[2]]

I have used the relevant theory: Newton's third law.[1]

I have used the relevant theory: normal force.[2]

d Since vertical forces are equal and opposite: $F_{net} = 1000 - 970 = 30$ N

e $a = \frac{F_{net}}{m} = \frac{30.0}{1000} = 3.00 \times 10^{-2}$ m s^{-2}

14 **a** Defining the positive directions as to the left and up:

Vertical components of forces sum to zero.

Component of each 700 N force in the horizontal direction:

$F_{horizontal} = 700 \times \cos(30°) = 606$ N

$F_{net} = 900 + 606 + 606 - 100$ N (1 MARK)

$F_{net} = 2.0 \times 10^3$ N to the left (2 MARKS)

b $a = \frac{F_{net}}{m} = \frac{2.01 \times 10^3}{70} = 29$ m s^{-2}

15 **a** When pushing: $F = -300 \times \sin(45°) = -212 = -2.1 \times 10^2$ N (1 MARK)

When pulling: $F = 300 \times \sin(45°) = 212 = 2.1 \times 10^2$ N (1 MARK)

b For forces in the vertical direction:

$F_g = 18 \times -9.8 = -176$ N (1 MARK)

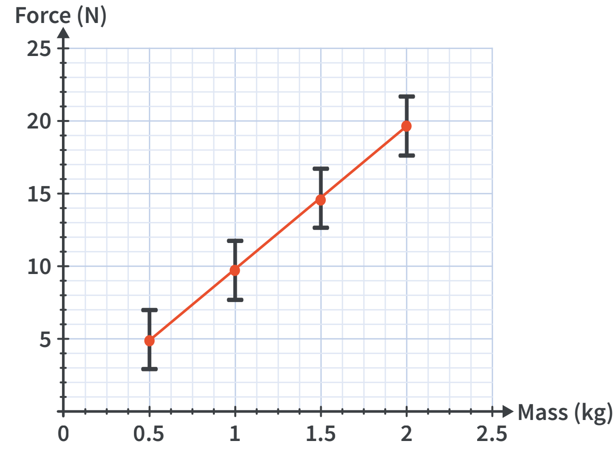
When pushing: $F_g + F_{Rami} = -176 - 212 = -3.9 \times 10^2$ N (1 MARK)

When pulling: $F_g + F_{Rami} = -176 + 212 = 36$ N (1 MARK)

c Because pulling yields an upwards vertical net force, Rami should pull the bin.

Key science skills

16 **a**



I have drawn a straight line of best fit.

I have drawn a line of best fit passing through all uncertainty bars.

b $g = \frac{F_g}{m} = \frac{rise}{run} = gradient$ (1 MARK)

From points on the line of best fit:

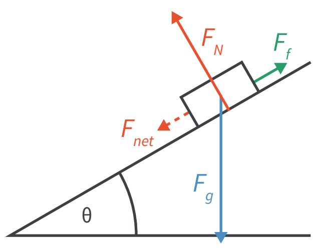
$g = \frac{rise}{run} = \frac{19.5 - 5.0}{2.0 - 0.5} = 9.7$ m s^{-2} (1 MARK)

2C Inclined planes and connected bodies

Theory review questions

1 B

2



3 D

4 A

Exam-style questions

This lesson

5 **a** $F_N = mg\cos(\theta) = 5.0 \times 9.8 \times \cos(15°)$ (1 MARK)

$F_N = 47$ N (1 MARK)

b $F_{net} = F_{ds} - F_f = mg\sin(\theta) - 0$ (1 MARK)

$F_{net} = 5.0 \times 9.8 \times \sin(15°) = 12.7 = 13$ N (1 MARK)

c $F_{net} = ma \therefore 12.7 = 5.0 \times a$

$a = 2.5$ m s^{-2}

6 **a** $F_{net} = ma = 1500 \times 1.20 = 1.80 \times 10^3$ N b As tension is the only force acting on the trailer

$F_{net\ trailer} = T = m_{trailer}a$ (1 MARK)

$T = 700 \times 1.20 = 840$ N (1 MARK)

7 a $F_{g\ m2} = m_2g = 0.25 \times 9.8 = 2.45$ N (1 MARK)

$F_{net} = F_{g\ m2} - F_f = ma \therefore 2.45 - 0.50 = (0.25 + 0.50) \times a$

$a = 2.6$ m s^{-2} (1 MARK)

b $F_{net\ m1} = T - F_f = m_1a \therefore T - 0.50 = 0.50 \times 2.6$ (1 MARK)

$T = 1.8$ N (1 MARK)

8 a $F_{net} = ma \therefore 80 = (2.0 + 6.0) \times a$

$a = 10$ m s^{-2} (1 MARK)

$F_{net\ A} = ma = 2.0 \times 10 = 20$ N

$F_{net\ A} = 80 - F_{on\ A\ by\ B} \therefore 20 = 80 - F_{on\ A\ by\ B}$ (1 MARK)

$F_{on\ A\ by\ B} = 60$ N (1 MARK)

b $F_{on\ B\ by\ A} = 60$ N (1 MARK)

$F_{on\ B\ by\ A}$ is to the right by Newton's third law. (1 MARK)

9 a $F_{net} = T_1 - F_f - F_f = 0 \therefore T_1 - 100 - 100 = 0 \therefore T_1 = 200$ N

b $F_{net\ pyramid\ 2} = T_2 - F_f = ma \therefore T_2 - 100 = 250 \times 0.25$ (1 MARK)

$T_2 = 163 = 1.6 \times 10^2$ N (1 MARK)

$F_{net\ pyramid\ 1} = T_1 - T_2 - F_f = ma \therefore T_1 - 163 - 100 = 250 \times 0.25$ (1 MARK)

$T_1 = 326 = 3.3 \times 10^2$ N (1 MARK)

c Rope 1 will break before rope 2 as it has to pull both pyramids. (1 MARK)

Consider the two pyramids: $F_{net} = T_{1\ break} - F_f - F_f = ma$

$1800 - 100 - 100 = 500 \times a$ (1 MARK)

$a = 3.2$ m s^{-2} (1 MARK)

10 a For block A: $F_{net} = 0 = F_{on\ A\ by\ B} - F_g$ (1 MARK)

$F_{on\ A\ by\ B} = F_g = m_Ag = 2.0 \times 9.8 = 19.6 = 20$ N upwards (1 MARK)

b $F_{on\ A\ by\ B} = 0$ N

Note that since the blocks are now accelerating at g, the only force acting on each block is $F_g = mg$. So the contact force must be zero.

11 a $F_{net} = F_{ds} - F_f = mg\sin(\theta) - 0$

$F_{net} = 20.0 \times 9.8 \times \sin(30.0°) = 98$ N (1 MARK)

$F_{net} = ma \therefore 98 = 20 \times a$

$a = 4.9$ m s^{-2} (1 MARK)

b $F_{net} = ma = 20.0 \times 0.50 = 10$ N (1 MARK)

$F_{net} = F_{ds} - F_f = mg\sin(\theta) - F_f$

$10 = 20.0 \times 9.8 \times \sin(30.0°) - F_f$ (1 MARK)

$F_f = 88$ N (1 MARK)

Previous lessons

12 a $F_{ds} = mg\sin(\theta) = 0.50 \times 9.8 \times \sin(30.0°) = 2.45$ N (1 MARK)

$F_{net} = F_{ds} = ma \therefore 2.45 = 0.50 \times a$

$a = 4.9$ m s^{-2} (1 MARK)

b $v^2 = u^2 + 2as = 0^2 + 2 \times 4.9 \times 10.0$ (1 MARK)

$v = 9.9$ m s^{-1} (1 MARK)

c $F_{net} = F_f = ma \therefore -0.75 = 0.50 \times a$

$a = -1.5$ m s^{-2} (1 MARK)

$v^2 = u^2 + 2as \therefore 0^2 = 9.9^2 + 2 \times -1.5 \times s$ (1 MARK)

$s = 33$ m (1 MARK)

d 'The force on the ground by the ball'.

Key science skills questions

13 [Random errors will be present due to the difficulty of measuring a moving object between the 5 cm gradation lines of the ruler.[1]][Its significance can be reduced by repeating the experiment multiple times and taking the average of the measurements[2]][or using a more precise measurement method such as a slow-motion camera.[3]]

- I have used the relevant theory: random errors.[1]
- I have explicitly addressed one way to reduce the error.[2]
- I have explicitly addressed another way to reduce the error.[3]

2D Basic circular motion

Theory review questions

1 B 2 C 3 B 4 A

Exam-style questions

This lesson

5 a A b G c C d F

e B f D

6 $a = \frac{v^2}{r} = \frac{16^2}{1.5} = 1.7 \times 10^2$ m s^{-2}

7 $F = m \times \frac{4\pi^2 r}{T^2} = 15\,000 \times \frac{4 \times \pi^2 \times 45.0}{30.0^2} = 2.96 \times 10^4$ N

8 a $a = \frac{v^2}{r} = \frac{8.00^2}{50.0} = 1.28$ m s^{-2}

b $F = \frac{mv^2}{r} = \frac{55.0 \times 8.00^2}{50.0} = 70.4$ N

9 a 8 revolutions per second, therefore $T = \frac{1}{8.00} = 0.125$ s (1 MARK)

$v = \frac{2\pi r}{T} = \frac{2 \times \pi \times 12.0}{0.125} = 603$ m s^{-1} (1 MARK)

b To the right

10 a $v = \frac{36}{3.6} = 10$ m s^{-1} (1 MARK)

$a = \frac{v^2}{r} = \frac{10^2}{60} = 1.7$ m s^{-2} (1 MARK)

b $F = \frac{mv^2}{r} = \frac{600 \times 10^2}{60} = 1.0 \times 10^3$ N

11 $v = \frac{2\pi r}{T}$ $\therefore 15 = \frac{2 \times \pi \times 5.0}{T}$ (1 MARK)

$T = 2.09$ s (1 MARK)

$\text{Time} = \frac{T}{4} = \frac{2.09}{4} = 0.52$ s (1 MARK)

12 **a** $r = 2.30 \times 10^7 + 3.00 \times 10^6 = 2.60 \times 10^7$ m (1 MARK)

$T = 30.0 \times 60 \times 60 = 1.08 \times 10^5$ s (1 MARK)

$v = \frac{2\pi r}{T} = \frac{2 \times \pi \times 2.60 \times 10^7}{1.08 \times 10^5} = 1.51 \times 10^3$ m s^{-1} (1 MARK)

b $a = \frac{4\pi^2 r}{T^2} = \frac{4 \times \pi^2 \times 2.60 \times 10^7}{(1.08 \times 10^5)^2} = 8.80 \times 10^{-2}$ m s^{-2}

c $v = \frac{2\pi r}{T}$ $\therefore 2.00 \times 10^3 = \frac{2 \times \pi \times r}{8.00 \times 60 \times 60}$ (1 MARK)

$r = 9.17 \times 10^6$ m (1 MARK)

Orbital height $= 9.17 \times 10^6 - 3.00 \times 10^6 = 6.17 \times 10^6$ m (1 MARK)

13 Net force on the ball is the tension. $\therefore T = \frac{mv^2}{r}$ (1 MARK)

$3.0 = \frac{0.30 \times v^2}{0.80}$ $\therefore v = 2.8$ m s^{-1} (1 MARK)

Previous lessons

14 $F_{ds} = mg\sin(\theta) = 1.5 \times 9.8 \times \sin(15°) = 3.80$ N (1 MARK)

$F_{net} = ma$ $\therefore 3.80 = 1.5 \times a$ $\therefore a = 2.54$ m s^{-2} (1 MARK)

$v^2 = u^2 + 2as$ $\therefore v^2 = 0^2 + 2 \times 2.54 \times 2.0$ (1 MARK)

$v = 3.2$ m s^{-1} (1 MARK)

15 **a** Normal force

b $F_g = mg = 20.0 \times 9.8 = 196$ N (1 MARK)

$F_{N\,per\,leg} = \frac{F_g}{4} = \frac{196}{4} = 49$ N (1 MARK)

Key science skills

16 [The uncertainty in this measuring device is half the smallest increment on the ruler.[1]][The smallest increment is 0.5 cm so the uncertainty is 0.25 cm.[2]]

- I have explicitly addressed how to calculate the uncertainty.[1]
- I have calculated the uncertainty.[2]

2E Banked circular motion

Theory review questions

1 D **2** B **3** D **4** B

Exam-style questions

This lesson

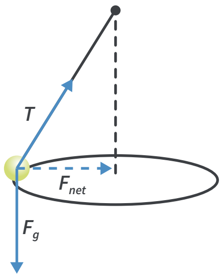
5 **a** $v = \sqrt{rg\tan(\theta)} = \sqrt{40 \times 9.8 \times \tan(35°)}$ (1 MARK)

$v = 17$ m s^{-1} (1 MARK)

b $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{20^2}{40 \times 9.8}\right)$ (1 MARK)

$\theta = 46°$ (1 MARK)

6 **a**



- I have drawn the tension vector in the direction of the string away from the mass.
- I have drawn the force due to gravity vector straight down from the centre of the mass.
- I have drawn the net force vector radially inwards (to the centre of the circular path).
- I have drawn the size of the tension and force due to gravity vectors so that they add to the net force vector.

b $T = \sqrt{(F_{net})^2 + (F_g)^2} = \sqrt{\left(\frac{mv^2}{r}\right)^2 + (mg)^2}$

$T = \sqrt{\left(\frac{1.2 \times 2.0^2}{0.60}\right)^2 + (1.2 \times 9.8)^2}$ (1 MARK)

$T = 14$ N (1 MARK)

c $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{1.5^2}{0.60 \times 9.8}\right)$ (1 MARK)

$\theta = 21°$ (1 MARK)

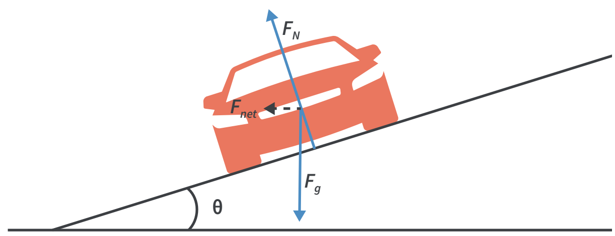
7 **a** $v = \sqrt{rg\tan(\theta)}$ $\therefore 40 = \sqrt{r \times 9.8 \times \tan(50°)}$ $\therefore r = \frac{40^2}{9.8 \times \tan(50°)}$ (1 MARK)

$r = 1.4 \times 10^2$ m (1 MARK)

b $v = \sqrt{rg\tan(\theta)} = \sqrt{80 \times 9.8 \times \tan(50°)}$ (1 MARK)

$v = 31$ m s^{-1} (1 MARK)

c



- I have drawn the normal force vector perpendicular to the slope of the track from the track surface.
- I have drawn the force due to gravity vector straight down from the centre of the vehicle.
- I have drawn the net force vector with a dashed arrow pointing horizontally to the left.
- I have drawn the size of the force due to gravity and normal force vectors so that the resultant vector matches the net force vector.

d $F_{net} = \frac{mv^2}{r} = \frac{2000 \times 40^2}{80} = 4.0 \times 10^4$ N

e $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{40^2}{80 \times 9.8}\right)$ (1 MARK)

$\theta = 64°$ (1 MARK)

8 a $\theta = \sin^{-1}\left(\frac{opposite}{hypotenuse}\right) = \sin^{-1}\left(\frac{0.40}{0.70}\right) = 34.8°$ (1 MARK)

$F_{net} = F_g \tan(\theta) = mg\tan(\theta) = 0.30 \times 9.8 \times \tan(34.8°) = 2.0$ N (1 MARK)

b $T = \sqrt{(F_{net})^2 + (mg)^2} = \sqrt{2.0^2 + (0.30 \times 9.8)^2}$ (1 MARK)

$T = 3.6$ N (1 MARK)

OR

$T = \frac{F_{net}}{\sin(\theta)} = \frac{2.0}{\sin(34.8°)}$ (1 MARK)

$T = 3.6$ N (1 MARK)

OR

$T = \frac{mg}{\cos(\theta)} = \frac{0.30 \times 9.8}{\cos(34.8°)}$ (1 MARK)

$T = 3.6$ N (1 MARK)

Previous lessons

9 a $a = \frac{4\pi^2 r}{T^2} = \frac{4 \times \pi^2 \times 0.60}{1.4^2}$ (1 MARK)

$a = 12$ m s^{-2} (1 MARK)

b $F_{net} = ma = 0.20 \times 12 = 2.4$ N

10 $F_{net} = F_{ds} = mg\sin(\theta) = 0.30 \times 9.8 \times \sin(10°) = 0.511$ N (1 MARK)

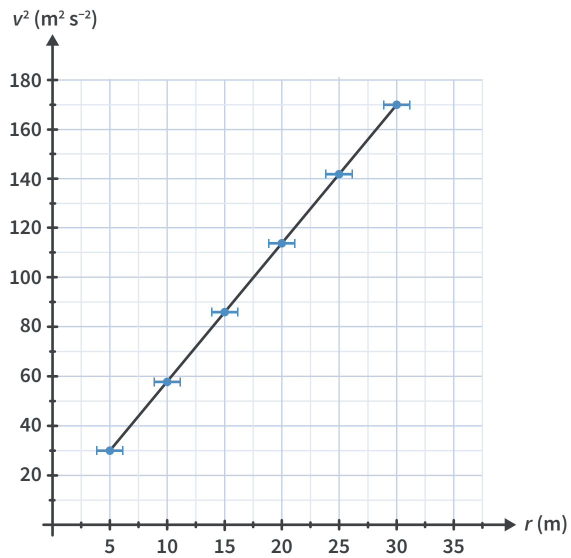
$F_{net} = ma \therefore a = \frac{F_{net}}{m} = \frac{0.511}{0.30} = 1.70$ m s^{-2} (1 MARK)

$v^2 = u^2 + 2as = 0 + 2 \times 1.70 \times 2.0 = 6.8 \therefore v = 2.6$ m s^{-1} (1 MARK)

Key science skills

11 a 28.3, 56.6, 84.8, 112, 142, 169

b



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 axes.

I have plotted each point of data.

I have drawn correctly sized uncertainty bars.

I have drawn a straight line of best fit which passes through all uncertainty bars.

c $Gradient = \frac{y_2 - y_1}{x_2 - x_1}$

Use two points on the line of best fit that are far apart.

$Gradient = 5.6$ (1 MARK)

Depending on the line of best fit drawn, values between 5.1 and 6.2 are acceptable.

$Gradient = \frac{v^2}{r} = g\tan(\theta) \therefore \theta = \tan^{-1}\left(\frac{Gradient}{g}\right)$ (1 MARK)

$\theta = \tan^{-1}\left(\frac{5.6}{9.8}\right) = 30°$ (1 MARK)

2F Vertical circular motion

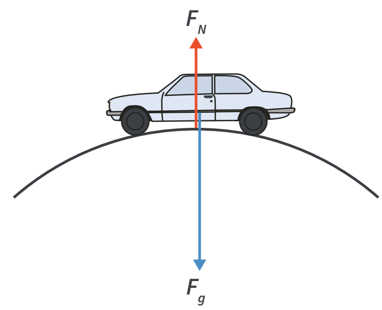
Theory review questions

1 D **2** B **3** D **4** A

Exam-style questions

This lesson

5 a



I have drawn all forces acting upon the car.

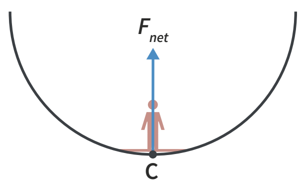
I have labelled all forces acting upon the car correctly.

I have shown the force due to gravity to be greater in magnitude than the normal force.

b $\frac{mv^2}{r} = mg \therefore v = \sqrt{gr} = \sqrt{9.8 \times 5.2}$ (1 MARK)

$v = 7.1$ m s^{-1} (1 MARK)

6 a



I have drawn a force vector pointing in the right direction.

I have correctly labelled the net force vector.

b $F_{net} = F_N - F_g$

$\frac{mv^2}{r} = F_N - mg \therefore \frac{60 \times 18^2}{15} = F_N - 60 \times 9.8$ (1 MARK)

$F_N = 1.9 \times 10^3$ N (1 MARK)

7 **a** $v = \sqrt{gr} \therefore 12.0 = \sqrt{9.8 \times r}$ (1 MARK)

$r = 15$ m (1 MARK)

b [There is always a force due to gravity acting on the motorcyclist,[1]] [however, as the velocity is minimised the motorcyclist experiences no normal force.[2]] [This is perceived as zero gravity.[3]]

- I have explicitly addressed the force due to gravity at the top of the loop.[1]
- I have explicitly addressed the normal force.[2]
- I have used the relevant theory: zero normal force.[3]

c $\frac{mv^2}{r} = F_g + F_N = mg + F_N \therefore \frac{80 \times 16.0^2}{12.0} = 80 \times 9.8 + F_N$ (1 MARK)

$F_N = 9.2 \times 10^2$ N (1 MARK)

8 Calculate the minimum speed the cart needs to stay on the track.

$v = \sqrt{gr} = \sqrt{9.8 \times 13.0}$ (1 MARK)

$v = 11 \text{ m s}^{-1} > 9.0 \text{ m s}^{-1}$ (1 MARK)

No. The cart will fall off the track if it is not supported by an upwards force. (1 MARK)

9 **a** $v = \sqrt{gr} = \sqrt{9.8 \times 1.2}$ (1 MARK)

$v = 3.4 \text{ m s}^{-1}$ (1 MARK)

b $\frac{mv^2}{r} = T - mg \therefore \frac{3.2 \times 7.3^2}{1.2} = T - 3.2 \times 9.8$ (1 MARK)

$T = 1.7 \times 10^2 > 150$ N (1 MARK)

The string will break. (1 MARK)

Previous lessons

10 $m_{tot} = 10 + 20 + 5 = 35$ kg

$F_{net} = m_{tot}a \therefore 200 = 35 \times a$ (1 MARK)

$a = 5.71 \text{ m s}^{-2}$ (1 MARK)

$F_{on\ C\ by\ B} = m_C a = 5.0 \times 5.71 = 29$ N (1 MARK)

11 $F = \frac{mv^2}{r} \therefore 12 = \frac{0.40 \times v^2}{0.75}$ (1 MARK)

$v = 4.7 \text{ m s}^{-1}$ (1 MARK)

Key science skills

12 **a** [v^2 should be placed on the vertical axis[1]] [as it is the dependent variable.[2]] [r should be graphed on the horizontal axis[3]] [as it is the independent variable.[4]]

- I have explicitly addressed the axis on which v^2 should be graphed.[1]
- I have used the relevant theory: dependent variables.[2]
- I have explicitly addressed the axis on which r should be graphed.[3]
- I have used the relevant theory: independent variables.[4]

b D. The gradient is equal to $\frac{rise}{run} = \frac{v^2}{r}$. For zero normal force (when the cart loses contact with the track), $v = \sqrt{gr}$ so the gradient $\frac{v^2}{r} = g \approx 9.8 \text{ m s}^{-2}$.

2G Projectile motion

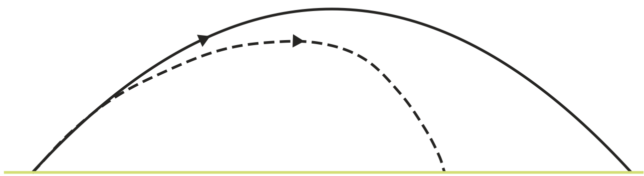
Theory review questions

1 C **2** A **3** A **4** B **5** D

Exam-style questions

This lesson

6



- I have drawn a curve with a shorter horizontal range.
- I have drawn a curve with a lower maximum height.
- I have drawn an asymmetrical graph with the rising slope less steep than the falling slope.

7 **a** $v_y{}^2 = u_y{}^2 + 2as \therefore 0 = u_y{}^2 + 2 \times (-9.8) \times 49$ (1 MARK)

$u_y = \pm 31 \text{ m s}^{-1}$. Take positive value since we know the rocket is travelling upwards.

$u_y = 31 \text{ m s}^{-1}$ upwards. (1 MARK)

b Vertical motion: $s_y = u_y t + \frac{1}{2}at^2 \therefore 0 = 31 \times t + \frac{1}{2} \times (-9.8) \times t^2$ (1 MARK)

$t = 6.32$ s (1 MARK)

$t = 0$ is also a solution to the equation but it describes the time when the rocket leaves the ground, rather than when it lands.

$u_y = u\sin(\theta) \therefore 31 = u \times \sin(80°) \therefore u = 31.5 \text{ m s}^{-1}$

Horizontal motion: $v_x = u\cos(\theta) = 31.5 \times \cos(80°) = 5.47 \text{ m s}^{-1}$

$v_x = \frac{s_x}{t} \therefore 5.47 = \frac{s_x}{6.32}$

$s_x = 35$ m (1 MARK)

8 **a** $u_y = u\sin(\theta) = 32.0 \times \sin(50°) = 24.51 \text{ m s}^{-1}$

$v_y{}^2 = u_y{}^2 + 2as_y \therefore 0 = 24.51^2 + 2 \times (-9.8) \times s_y$ (1 MARK)

$s_y = 31$ m (1 MARK)

OR

$v_y = u_y + at \therefore 0 = 24.51 + (-9.8) \times t$

$t = 2.50$ s (1 MARK)

$s_y = v_y t - \frac{1}{2}at^2 = 0 \times 2.50 - \frac{1}{2} \times (-9.8) \times 2.50^2$

$s_y = 31$ m (1 MARK)

b Horizontal motion: $v_x = u\cos(\theta) = 32.0 \times \cos(50°) = 20.57$ m s^{-1}

$v_x = \frac{s_x}{t}$ $\therefore 20.57 = \frac{90}{t}$

$t = 4.375$ s (1 MARK)

Vertical motion:

$s_y = u_y t + \frac{1}{2}at^2 = 24.51 \times 4.375 + \frac{1}{2} \times (-9.8) \times 4.375^2$ (1 MARK)

$s_y = 13$ m (1 MARK)

c $t_{final} = 2 \times t_{max\ height} = 2 \times 2.50 = 5.00$ s, by symmetry. (1 MARK)

$v_x = \frac{s_x}{t}$ $\therefore 20.57 = \frac{s_x}{5.0}$

$s_x = 103 = 1.0 \times 10^2$ m (1 MARK)

9 a Vertical motion: $s_y = u_y t + \frac{1}{2}at^2$ $\therefore 1.2 = 0 \times t + \frac{1}{2} \times (-9.8) \times t^2$ (1 MARK)

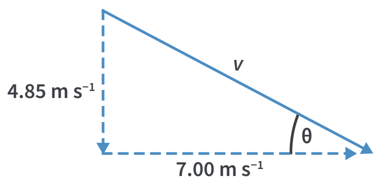
$t = 0.495$ s (1 MARK)

Horizontal motion: $v_x = \frac{s_x}{t}$ $\therefore 7.00 = \frac{s_x}{0.495}$

$s_x = 3.5$ m (1 MARK)

b Vertical motion: $v_y = u_y + at$ $\therefore v_y = 0 + (-9.8) \times 0.495$

$v_y = -4.85$ m s^{-1} (1 MARK)



Find magnitude of velocity: $v^2 = v_y{}^2 + v_x{}^2 = (-4.85)^2 + 7.00^2$

$v = 8.5$ m s^{-1} (1 MARK)

Find direction of velocity: $\theta = \tan^{-1}\left(\frac{4.85}{7.00}\right) = 34.7° = 35°$ below the horizontal. (1 MARK)

10 a $s_y = u_y t + \frac{1}{2}at^2 = 0 \times 5.0 + \frac{1}{2} \times (-9.8) \times 5.0^2$ (1 MARK)

$s_y = -122.5 = -1.2 \times 10^2$ m. The height is 1.2×10^2 m. (1 MARK)

b $v_x = \frac{s_x}{t} = \frac{280}{5.0} = 56$ m s^{-1}

11 a $u_y = u\sin(\theta) = 75 \times \sin(40°) = 48.2$ m s^{-1}

$v_y{}^2 = u_y{}^2 + 2as$ $\therefore 0 = 48.2^2 + 2 \times (-9.8) \times d$ (1 MARK)

$d = 1.2 \times 10^2$ m (1 MARK)

b Vertical motion: $s_y = u_y t + \frac{1}{2}at^2$ $\therefore 0 = 48.2 \times t + \frac{1}{2} \times (-9.8) \times t^2$ (1 MARK)

$t = 9.84$ s (1 MARK)

$t = 0$ is also a solution to the equation but it describes the time when the stone is launched, rather than when it reaches point A.

Horizontal motion: $v_x = u\cos(\theta) = 75 \times \cos(40°) = 57.5$ m s^{-1}

$v_x = \frac{s_x}{t}$ $\therefore 57.5 = \frac{s_x}{9.84}$

$s_x = 5.7 \times 10^2$ m (1 MARK)

c Vertical motion: $v_y{}^2 = u_y{}^2 + 2as$ $\therefore v_y{}^2 = (48.2)^2 + 2 \times (-9.8) \times (-62)$ (1 MARK)

$v_y = \pm 59.5$ m s^{-1}. Take negative value since we know the stone is travelling downwards.

$v^2 = v_x{}^2 + v_y{}^2 = 57.5^2 + (-59.5)^2$ (1 MARK)

$v = 83$ m s^{-1} > 70 m s^{-1} $\therefore$ the boat will sink. (1 MARK)

Previous lessons

12 For circular motion, $F_{net} = \frac{mv^2}{r} = \frac{1200 \times 40^2}{20}$ (1 MARK)

$F_{net} = 9.6 \times 10^4$ N towards the centre of the circle of motion (1 MARK)

13 At the minimum speed, the gravitational force is the only force providing centripetal acceleration.

$F_N + mg = \frac{mv^2}{r}$ $\therefore 0 + 400 \times 9.8 = \frac{400 \times v^2}{9.0}$ (1 MARK)

$v = 9.4$ m s^{-1} (1 MARK)

Key science skills

14 a [Achol produced precise but inaccurate results.[1]][The results are precise because there is not much variation between her results (the range is 0.4 s)[2]][but they are not very accurate because the true value (12.0 s) is not within the range of her results, and significantly differs from her average (10.2 s).[3]]

- I have explicitly identified which student produced precise but inaccurate results.[1]
- I have used the relevant theory: precision.[2]
- I have used the relevant theory: accuracy.[3]

b [Random errors have had a less significant effect than systematic errors[1]][since the variation between measurements is less significant[2]][than the difference between measurements and the true value.[3]]

- I have explicitly addressed the effect of random errors and systematic errors.[1]
- I have used the relevant theory: random errors as a cause of variation in results.[2]
- I have used the relevant theory: systematic errors as cause of consistent deviation between results and a true value.[3]

Chapter 2 Review

Section A

1 C **2** D **3** B **4** A **5** C

Section B

6 Acceleration of the system:

$F_{net} = m_{total}a$ $\therefore 18 = (2.0 + 4.0) \times a$

$a = \frac{18}{(2.0 + 4.0)} = 3.0$ m s^{-2} (1 MARK)

Force on block Y by block X is the net force on block Y:

$F_{net} = m_Y a = 4.0 \times 3.0 = 12$ N (1 MARK)

7 a $v = u + at \;\therefore 10 = 0 + 0.50 \times t$ (1 MARK)

$t = 20$ s (1 MARK)

b Consider the trailer: $T - F_f = ma$

$T - 1000 = 600 \times 0.50$ (1 MARK)

$T = 1.3 \times 10^3$ N (1 MARK)

8 a $s = ut + \frac{1}{2}at^2 \;\therefore 1.5 = 0 \times 5.0 + \frac{1}{2} \times a \times 5.0^2$ (1 MARK)

$a = 0.12$ m s^{-2} (1 MARK)

b $F_{ds} = mg\sin(\theta) \;\therefore F_{ds} = 1.5 \times 9.8 \times \sin(20°) = 5.03$ N

$F_{net} = ma \;\therefore 5.03 - F_f = 1.5 \times 0.12$ (1 MARK)

$F_f = 4.8$ N (1 MARK)

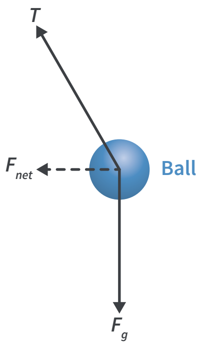
9 a Consider the whole system:

$F_{net} = m_2 g = 0.50 \times 9.8 = 4.9$ N (1 MARK)

$a = \frac{F_{net}}{m_{total}} = \frac{4.9}{(2.0 + 0.50)} = 1.96 = 2.0$ m s^{-2} (1 MARK)

b Consider m_1: $T = F_{net} = m_1 a = 2.0 \times 1.96 = 3.9$ N

10 a



- I have drawn an arrow to represent the tension force at the same angle as the string in the question diagram.
- I have drawn an arrow to represent the force of gravity pointing straight down and starting at the centre of the ball.
- I have drawn a dashed arrow to represent the net force pointing horizontally left.
- I have drawn all forces with appropriate magnitudes: the tension force arrow has the same horizontal length as the net force arrow.
- I have drawn all forces with appropriate magnitudes: the tension force arrow has the same vertical length as the force due to gravity arrow.
- I have labelled all forces appropriately.

b $T = \sqrt{(F_{net})^2 + (F_g)^2} = \sqrt{\left(\frac{mv^2}{r}\right)^2 + (mg)^2}$ (1 MARK)

$T = \sqrt{\left(\frac{0.50 \times 1.2^2}{0.40}\right)^2 + (0.50 \times 9.8)^2}$ (1 MARK)

$T = 5.2$ N (1 MARK)

OR

$\sin(\theta) = \frac{0.40}{1.16} = 0.345$ (1 MARK)

$\sin(\theta) = \frac{F_{net}}{T} = \frac{mv^2/r}{T} \;\therefore 0.345 = \frac{0.50 \times 1.2^2/0.40}{T}$ (1 MARK)

$T = 5.2$ N (1 MARK)

11 a Vertical motion: $s = ut + \frac{1}{2}at^2 \;\therefore 1.5 = 0 \times t + \frac{1}{2} \times 9.8 \times t^2$ (1 MARK)

$t = 0.553$ s (1 MARK)

Horizontal motion: $v = \frac{\Delta s}{\Delta t} \;\therefore 6.0 = \frac{\Delta s}{0.553}$

$\Delta s = 3.3$ m (1 MARK)

b Vertical motion: $v^2 = u^2 + 2as = 0^2 + 2 \times 9.8 \times 1.5$

$v = 5.42$ m s^{-1} (1 MARK)

Speed $= \sqrt{5.42^2 + 6.0^2} = 8.1$ m s^{-1} (1 MARK)

The M&M will shatter when it hits the ground. (1 MARK)

12 a $F_{net} = \frac{mv^2}{r} = \frac{85 \times 14^2}{45} = 3.7 \times 10^2$ N (1 MARK)

The net force acts radially inwards **OR** horizontally towards the centre of the banked track. (1 MARK)

b $\tan(\theta) = \frac{v^2}{rg} = \frac{14^2}{45 \times 9.8}$ (1 MARK)

$\theta = 24°$ (1 MARK)

13 a $F_{ds} = mg\sin(\theta) = 1.50 \times 9.8 \times \sin(45°) = 10.4$ N (1 MARK)

$F_{net} = ma \;\therefore 10.4 = 1.50 \times a$

$a = 6.9$ m s^{-2} (1 MARK)

b $\sin(\theta) = \frac{opposite}{hypotenuse} \;\therefore \sin(45°) = \frac{15}{hypotenuse}$

$hypotenuse = ramp\ length = 21.2$ m (1 MARK)

$v^2 = u^2 + 2as \;\therefore v^2 = 0^2 + 2 \times 6.9 \times 21.2$ (1 MARK)

$v = 17$ m s^{-1} (1 MARK)

c $v = \sqrt{rg} = \sqrt{3.0 \times 9.8} = 5.4$ m s^{-1}

d $F_{net} = F_g + F_N \;\therefore F_N = \frac{mv^2}{r} - mg = \frac{1.50 \times 13^2}{3.0} - 1.50 \times 9.8$ (1 MARK)

$F_N = 70$ N (1 MARK)

14 a $v^2 = u^2 + 2as \;\therefore 0^2 = (50 \times \sin(40°))^2 + 2 \times (-9.8) \times s$ (1 MARK)

$s = 53$ m (1 MARK)

b $v = \frac{\Delta s}{\Delta t} \;\therefore 50 \times \cos(40°) = \frac{180}{\Delta t}$ (1 MARK)

$\Delta t = 4.7$ s (1 MARK)

c Horizontal motion: $v = 50 \times \cos(40°)$ m s^{-1}

Vertical motion:

$v = u + at = 50 \times \sin(40°) - 9.8 \times 4.7 = -13.9$ m s^{-1} (1 MARK)

Speed $= \sqrt{(50 \times \cos(40°))^2 + (-13.9)^2} = 41$ m s^{-1} (1 MARK)

d $s = ut + \frac{1}{2}at^2 = 50 \times \sin(40°) \times 4.7 + \frac{1}{2} \times (-9.8) \times 4.7^2$ (1 MARK)

$s = 43$ m (1 MARK)

The village man should not take the bet as the stone will not make it over the wall. (1 MARK)

3A Momentum and impulse

Theory review questions

1 B and C **2** A **3** D **4** C **5** B

Exam-style questions

This lesson

6 $p = mv = 0.25 \times 4.0 = 1.0$ kg m s^{-1} (1 MARK)

$p = 1.0$ kg m s^{-1} or N s to the right (1 MARK)

7 $p = mv \;\therefore 0.50 = 0.20 \times v$ (1 MARK)

$v = 2.5$ m s^{-1} (1 MARK)

8 **a** $I = \Delta p = m\Delta v = 1500 \times (0 - 50)$ (1 MARK)

$I = -7.5 \times 10^4 = 7.5 \times 10^4$ kg m s^{-1} or N s (1 MARK)

b $I = F_{avg}\Delta t \;\therefore 7.5 \times 10^4 = F_{avg} \times 8.5$ (1 MARK)

$F_{avg} = 8.8 \times 10^3$ N (1 MARK)

9 **a** Due to the conservation of momentum: $p_i = p_f$

$p_f = p_{car} + p_{truck} = m_1u_1 + m_2u_2 = 1.5 \times 10^3 \times 20 + 7.5 \times 10^3 \times 10$

$p_f = 1.05 \times 10^5 = 1.1 \times 10^5$ kg m s^{-1} or N s to the right (2 MARKS)

b $p_f = m_{tot}v \;\therefore 1.05 \times 10^5 = (1.5 \times 10^3 + 7.5 \times 10^3) \times v$ (1 MARK)

$v = 11.7 = 12$ m s^{-1} (1 MARK)

c Taking the right as positive

$I = \Delta p = m\Delta v = 1.5 \times 10^3 \times (11.7 - 20) = -1.3 \times 10^4$ (1 MARK)

$I = 1.3 \times 10^4$ kg m s^{-1} or N s to the left (2 MARKS)

d Impulse will be equal in magnitude and opposite in direction due to Newton's third law.

The impulse on the truck by the car will be 1.3×10^4 kg m s^{-1} or N s to the right (2 MARKS)

10 $I = F_{avg}\Delta t \;\therefore 2.90 = F_{avg} \times 0.010$ (1 MARK)

$F_{avg} = 2.9 \times 10^2$ N (1 MARK)

11 **a** Taking the right as positive

$I = \Delta p = m\Delta v$ (1 MARK)

$I = 0.4 \times (55 - (-20)) = 30$ (1 MARK)

$I = 30$ kg m s^{-1} or N s (1 MARK)

b $I = F_{avg}\Delta t \;\therefore 30 = 1.2 \times 10^3 \times \Delta t$ (1 MARK)

$\Delta t = 0.025$ s (1 MARK)

Previous lessons

12 **a** $F_{net} = \dfrac{mv^2}{r} = \dfrac{110 \times 3.0^2}{8.0}$ (1 MARK)

$F_{net} = 1.2 \times 10^2$ N (1 MARK)

b

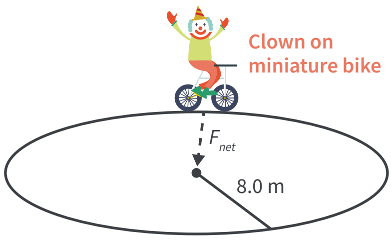


Image: Graphiqa Stock/Shutterstock.com

13 **a** Vertical motion:

$s = ut + \frac{1}{2}at^2 \;\therefore h = 0 \times 0.50 + \frac{1}{2} \times 9.8 \times 0.50^2$ (1 MARK)

$h = 1.23 = 1.2$ m (1 MARK)

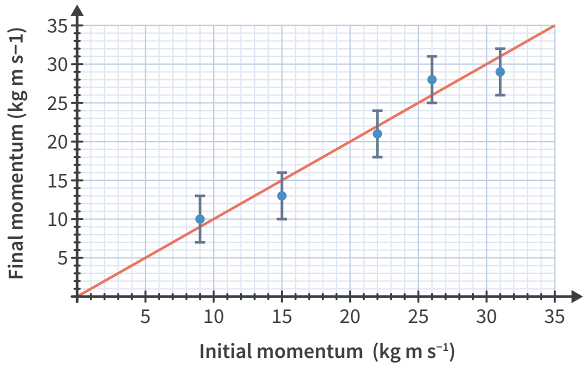
b Vertical motion:

$v = u + at = 0 + 9.8 \times 0.5$ (1 MARK)

$v = 4.9$ m s^{-1} (1 MARK)

Key science skills

14 **a**



- I have drawn initial momentum on the horizontal axis.
- I have drawn final momentum on the vertical axis.
- I have 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 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 students' data does support the law of conservation of momentum.[1]][It is possible to draw a line of best fit using the student's data that has a gradient of one,[2]][indicating that initial momentum is equal to final momentum.[3]]

- I have explicitly stated whether the data supports the law of conservation of momentum.[1]
- I have explicitly addressed a line of best fit with gradient one.[2]
- I have linked the gradient to the law of conservation of momentum.[3]

c They could use a slow motion camera **OR** electronic speed gun **OR** similar.

3B Kinetic energy, work and power

Theory review questions

1 C **2** B **3** C **4** B **5** C

Exam-style questions

This lesson

6 a $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$W = \frac{1}{2} \times 900 \times 10^2 - \frac{1}{2} \times 900 \times 0^2$ (1 MARK)

$W = 4.5 \times 10^4$ J (1 MARK)

b $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$W = \frac{1}{2} \times 900 \times 20^2 - \frac{1}{2} \times 900 \times 10^2$ (1 MARK)

$W = 1.4 \times 10^5$ J (1 MARK)

7 $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$10\,240 = \frac{1}{2} \times 80 \times v^2 - \frac{1}{2} \times 80 \times 12^2$ (1 MARK)

$v = 20$ m s^{-1} (1 MARK)

8 a $W = Fs = KE_f - KE_i$

$130 \times s = 13\,540 - 6000$ (1 MARK)

$s = 58.0$ m (1 MARK)

b $W = Fs = KE_f - KE_i$

$F \times 70 = 4900 - 9400$ (1 MARK)

$F = -64$ N

The negative indicates the force is in the opposite direction to the motion, but the magnitude of the force is 64 N. (1 MARK)

9 a $W = KE_f - KE_i \therefore Fs = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$800 \times s = \frac{1}{2} \times 1500 \times 14^2 - \frac{1}{2} \times 1500 \times 9.0^2$ (1 MARK)

$s = 1.1 \times 10^2$ m (1 MARK)

b $W = KE_f - KE_i \therefore Fs = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$F \times 64 = \frac{1}{2} \times 1200 \times 12^2 - \frac{1}{2} \times 1200 \times 20^2$ (1 MARK)

$F = 2.4 \times 10^3$ N (1 MARK)

10 [Let the kinetic energy for trial A be: $KE_A = \frac{1}{2}mv^2$. Then, kinetic energy for trial B is $KE_B = \frac{1}{2}m(3v)^2 = 9 \times \frac{1}{2}mv^2 = 9 \times KE_A$.[1]][Work is equal to the change in energy so the work done for trial B is 9 times the work done for trial A.[2]][Work is also given by $W = Fs$.[3]][Since the value of F (brake force) is the same for both cars, s (brake distance) must be 9 times greater for trial B.[4]]

- I have used the relevant theory: applied the KE formula to compare trial A and trial B.[1]
- I have used the relevant theory: work as a change in energy.[2]
- I have used the relevant theory: the relationship between work, force, and distance.[3]
- I have related my answer to the context of the question.[4]

11 Use the area under the graph: $W = 65\,000$ J (1 MARK)

$W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$65\,000 = \frac{1}{2} \times 1600 \times v^2 - \frac{1}{2} \times 1600 \times 8^2$ (1 MARK)

$v = 12$ m s^{-1} (1 MARK)

12 $W = 21\,000$ J (1 MARK)

$W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$u = 36$ km h^{-1} $= \frac{36}{3.6}$ m s^{-1} $= 10$ m s^{-1}

$21\,000 = \frac{1}{2} \times 1300 \times v^2 - \frac{1}{2} \times 1300 \times 10^2$ (1 MARK)

$v = 12$ m s^{-1} (1 MARK)

13 $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$W = \frac{1}{2} \times 80.0 \times \left(\frac{15.0}{3.6}\right)^2 - \frac{1}{2} \times 80.0 \times \left(\frac{10.0}{3.6}\right)^2$ (1 MARK)

$W = 386$ J (1 MARK)

$P = \frac{W}{\Delta t} = \frac{386}{3.00 \times 60} = 2.14$ W (1 MARK)

14 a $P = \frac{W}{\Delta t} \therefore 300 = \frac{W_{rem}}{30.0}$

$W_{rem} = 9000$ J (1 MARK)

$W = Fs \therefore 9000 = F_{rem} \times 15.0$ (1 MARK)

$F_{rem} = 600$ N (1 MARK)

b $F_{net} = F_{rem} - F_f \therefore 50.0 = 600 - F_f$

$F_f = 550$ N

c $E_{heat} = W_f = F_f s = 550 \times 15.0$ (1 MARK)

8.25×10^3 J dissipated as heat. (1 MARK)

Previous lessons

15 a $F_{net} = 0 \therefore T_B = 2.0 + 2.0 = 4.0$ N

b $T_A - F_{f,1} = m_1 a$

$T_A - 2.0 = 0.50 \times 0.80$ (1 MARK)

$T_A = 2.4$ N (1 MARK)

c The tension in string B will always be greater than in string A so it will break first.

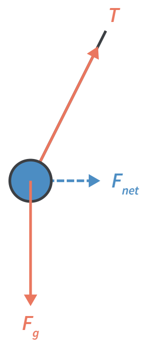
$m_{tot} a = T_B - F_{f,tot}$

$1.00 \times a = 10 - 4.0$ (1 MARK)

$a = 6$ m s^{-2} (1 MARK)

16 a $F_{net} = \frac{mv^2}{r} = \frac{0.15 \times 3.0^2}{5.0} = 0.27$ N

b



- I have drawn arrows for both the tension and the force due to gravity.
- I have drawn the net force as a horizontal dashed line which is pointing to the right.
- I have used appropriate lengths for the force vectors so that the net force is the vector sum of the tension and the force due to gravity.
- I have drawn the force due to gravity originating from the centre of the ball.

c [The net force on the ball is the vector sum of the tension force and the force due to gravity.[1]][The vertical component of the tension force balances the force due to gravity,[2]][so that the resultant (net) force is the horizontal component of the tension force.[3]]

- I have used the relevant theory: centripetal force and the net force.[1]
- I have explicitly addressed the forces in the vertical direction.[2]
- I have explicitly addressed the forces in the horizontal direction.[3]

d $v^2 = rg\tan(\theta)$ $\therefore 3.0^2 = 5.0 \times 9.8\tan(\theta)$ (1 MARK)

$\theta = 10°$ (1 MARK)

Key science skills

17 [Mikaela is correct. Sergio and Liam are incorrect.[1]][Random errors are unpredictable variations in the measurement process which create a spread of measured values and their effect can be reduced by taking an average of multiple measurements.[2]][Systematic errors cause measurements to differ from the true value by a consistent amount every time and can not be reduced by taking multiple measurements.[3]] [The uncertainty in each measurement is determined by the smallest deviations on the measuring instrument, so it cannot be changed by taking multiple measurements.[4]]

- I have explicitly addressed the correctness of each claim.[1]
- I have used the relevant theory: the relationship between random error and taking multiple measurements.[2]
- I have used the relevant theory: systematic error.[3]
- I have used the relevant theory: measurement uncertainty.[4]

3C Elastic and inelastic collisions

Theory review questions

1 B

2 A

Exam-style questions

This lesson

3 a Take motion to the right as positive.

$p_i = m_A u_A + m_B u_B = 110 \times 8.00 - 130 \times 5.00$

$p_i = 2.30 \times 10^2$ kg m s^{-1} or N s to the right

b $p_f = p_i = 2.30 \times 10^2$ kg m s^{-1} or N s to the right

c $p_f = m_{AB} v_{AB} = (110 + 130) \times v_{AB} = 2.30 \times 10^2$ (1 MARK)

$v_{AB} = 0.958$ m s^{-1} (1 MARK)

d $KE_{initial} = \frac{1}{2} m_A u_A{}^2 + \frac{1}{2} m_B u_B{}^2$ (1 MARK)

$KE_{initial} = \frac{1}{2} \times 110 \times 8.00^2 + \frac{1}{2} \times 130 \times 5.00^2 = 5.15 \times 10^3$ J (1 MARK)

e $KE_{final} = \frac{1}{2} m_{AB} v_{AB}{}^2 = \frac{1}{2} \times (110 + 130) \times 0.958^2 = 1.10 \times 10^2$ J

f Since $KE_i \neq KE_f$, the collision is inelastic

4 a Take motion to the right as positive.

Initial total momentum:

$p_i = m_X u_X + m_Y u_Y = 10 \times 10^3 \times 6.0 + 5.0 \times 10^3 \times 3.0$

$p_i = 75 \times 10^3$ kg m s^{-1} or N s (1 MARK)

Final total momentum:

$p_f = m_{XY} v_{XY} = 15 \times 10^3 \times v_{XY} = p_i = 75 \times 10^3$

$v_{XY} = 5.0$ m s^{-1} (1 MARK)

b $KE_{initial} = \frac{1}{2} m_X u_X{}^2 + \frac{1}{2} m_Y u_Y{}^2 = \frac{1}{2} \times 10 \times 10^3 \times 6.0^2 + \frac{1}{2} \times 5.0 \times 10^3 \times 3.0^2$

$KE_{initial} = 2.03 \times 10^5$ J (1 MARK)

$KE_{final} = \frac{1}{2} m_{XY} v_{XY}{}^2 = \frac{1}{2} \times 15 \times 10^3 \times 5.0^2 = 1.88 \times 10^5$ J (1 MARK)

Since $KE_i \neq KE_f$, the collision is inelastic (1 MARK)

5 By the conservation of momentum, if ball A is stationary after the collision, and the balls have equal mass, then ball B will have a speed of 4.0 m s^{-1}. (1 MARK)

$KE_{initial} = \frac{1}{2} m u_A{}^2 = \frac{1}{2} \times 0.35 \times 4.0^2 = 2.8$ J

$KE_{final} = \frac{1}{2} m v_B{}^2 = \frac{1}{2} \times 0.35 \times 4.0^2 = 2.8$ J (1 MARK)

Since $KE_i = KE_f$, the collision is elastic (1 MARK)

6 [Initially there is a net momentum to the right from the motion of the 4 kg block only.[1]][After the collision, the 4 kg block is moving to the left so the momentum of the 8 kg block (moving to the right) must be greater than the initial momentum of the 4 kg block[2]][for momentum to be conserved.[3]]

- I have used the relevant theory: momentum.[1]
- I have explicitly addressed why the 8 kg block has a greater momentum than the 4 kg block initially does.[2]
- I have used the relevant theory: conservation of momentum.[3]

7 $KE_{ball\,f} = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.048 \times 54.74^2 = 71.92$ J (1 MARK)

$\Delta KE_{club} = 71.92$ J (1 MARK)

$\Delta KE_{club} = KE_{club\,i} - KE_{club\,f} = \frac{1}{2}m_{club}u_{club}{}^2 - \frac{1}{2}m_{club}v_{club}{}^2$

$71.92 = \frac{1}{2} \times m_{club} \times 30.00^2 - \frac{1}{2} \times m_{club} \times 24.74^2$ (1 MARK)

$m_{club} = 0.50$ kg $= 5.0 \times 10^2$ g (1 MARK)

OR

$p_i = m_{club}u_{club} = 30.00 \times m_{club}$ (1 MARK)

$p_f = m_{club}v_{club} + m_{ball}v_{ball} = 24.74 \times m_{club} + 54.74 \times 0.048$ (1 MARK)

$p_i = p_f$

$24.74 \times m_{club} + 2.628 = 30.00 \times m_{club}$ (1 MARK)

$m_{club} = 0.50$ kg $= 5.0 \times 10^2$ g (1 MARK)

Previous lessons

8 a $v = \sqrt{rg\tan(\theta)} = \sqrt{50 \times 9.8 \times \tan(25°)} = 15$ m s^{-1}

b $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{30^2}{50 \times 9.8}\right) = 61°$

9 $I = m\Delta v$ (1 MARK)

$I = 0.25 \times 60 = 15$ kg m s^{-1} or N s (1 MARK)

Key science skills

10 5, 1, 3, 2, 1, 3.

11 [The gradient shown on this graph[1]][is constant and positive.[2]]

- I have explicitly addressed the gradient.[1]
- I have used the relevant theory: relationships between variables.[2]

3D Gravitational potential energy

Theory review questions

1 A 2 D 3 C 4 B

5 A 6 A

Exam-style questions

This lesson

7 a $\Delta GPE = mg\Delta h = 1800 \times 9.8 \times (0 - 15)$ (1 MARK)

$\Delta GPE = 2.6 \times 10^5$ J (1 MARK)

b $v = \sqrt{-2g\Delta h + u^2} = \sqrt{-2 \times 9.8 \times (15 - 0) + 30^2}$ (1 MARK)

$v = 25$ m s^{-1} (1 MARK)

8 a [Graph B.[1]][When the height is a maximum the ball has non-zero kinetic energy, and[2]][as the ball's height decreases it loses gravitational potential energy and its kinetic energy increases 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 initial kinetic energy at maximum height.[2]
- I have used the relevant theory: conservation of energy.[3]

b [Graph D.[1]][As the ball's height decreases its gravitational potential energy will also decrease since $GPE = mgh$.[2]]

- I have explicitly addressed which graph shows *GPE* as a function of gravitational potential energy.[1]
- I have used the relevant theory: relationship between height and gravitational potential energy.[2]

c $KE_i + GPE_i = KE_f + GPE_f \therefore \frac{1}{2}mu^2 + mgh_i = KE_f + mgh_f$

$\frac{1}{2} \times 0.50 \times 5.0^2 + 0.5 \times 9.8 \times 35 = KE_f + 0.50 \times 9.8 \times 0$ (1 MARK)

$KE_f = 1.8 \times 10^2$ J (1 MARK)

d $v = \sqrt{-2g\Delta h + u^2} = \sqrt{-2 \times 9.8 \times (10 - 35) + 5.0^2}$ (1 MARK)

$v = 23$ m s^{-1} (1 MARK)

9 a $W = Fs = 560 \times 18.2 = 10\,192$ J (1 MARK)

$W = \Delta GPE = mg\Delta h$

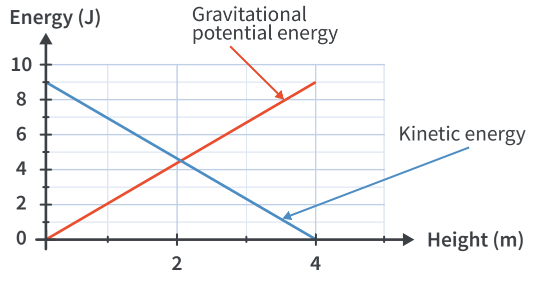
$10\,192 = 64 \times 9.8 \times \Delta h$ (1 MARK)

$\Delta h = 16$ m (1 MARK)

b [When moving over the dirt patch the skier's kinetic energy would be dissipated, for example into thermal energy.[1]][Since no energy has been created or destroyed (just transformed), energy is conserved.[2]]

- I have used the relevant theory: conservation of energy.[1]
- I have explicitly addressed if energy is conserved.[2]

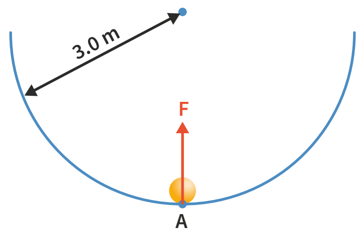
10



- I have drawn a straight line with an upwards slope labelled gravitational potential energy.
- I have drawn a straight line with a downwards slope labelled kinetic energy.
- I have drawn both lines up to but not passing a maximum energy of 9 J.
- I have drawn both lines up to but not exceeding a maximum height of 4 m.

Previous lessons

11 a



I have drawn an arrow pointing directly upwards from the point A.

b $F = m\frac{v^2}{r} + mg = 0.50 \times \frac{8.0^2}{3.0} + 0.50 \times 9.8$ (1 MARK)

$F = 16$ N (1 MARK)

12 a $I = \Delta p = p_i - p_f = 0.250 \times 13.0 - 0.250 \times 0$ (1 MARK)

$I = 3.25$ N s or kg m s^{-1} (2 MARKS)

b $I = F\Delta t \ \therefore 3.25 = F \times 0.150$ (1 MARK)

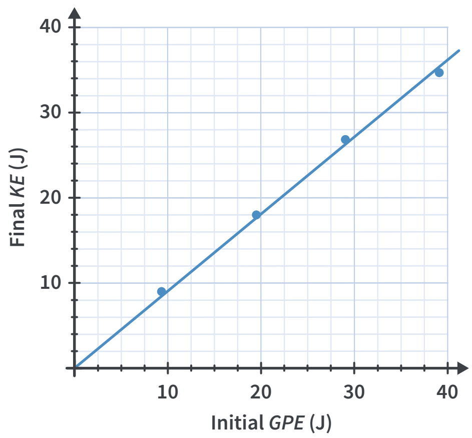
$F = 21.7$ N (1 MARK)

Key science skills

13 a

Height from which the ball is dropped (m)	Initial gravitational potential energy (J)	Final kinetic energy (J)
2	9.8	9.5
4	19.6	18
6	29.4	27
8	39.2	35

b



I have used the data to plot 4 points in the correct position.

I have labelled the horizontal axis as gravitational potential energy and given the units (joules).

I have labelled the vertical axis as kinetic energy and given the units (joules).

I have drawn a straight line of best fit.

3E Spring potential energy

Theory review questions

1 C **2** A **3** B **4** A

5 D **6** D

Exam-style questions

This lesson

7 a Gradient of graph $= \frac{100 - 0}{0.1 - 0} = 1000$ N m^{-1}

b From graph, $\Delta x = 0.04$ m

c $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 1000 \times (0.04)^2$ (1 MARK)

$SPE = 0.8$ J (1 MARK)

d $W = \Delta SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 1000 \times (0.080)^2$ (1 MARK)

$W = 3.2$ J (1 MARK)

e $W = \Delta KE = \frac{1}{2}mv^2$

$3.2 = \frac{1}{2} \times 3.0 \times v^2$ (1 MARK)

$v = 1.5$ m s^{-1} (1 MARK)

8 a $mg = k\Delta x$ (1 MARK)

$0.025 \times 9.8 = k \times (0.40 - 0.30) \ \therefore k = 2.45$ N m^{-1} (1 MARK)

b $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 2.45 \times (0.50 - 0.30)^2$ (1 MARK)

$SPE = 0.049$ J (1 MARK)

9 a $mg = k\Delta x \ \therefore 4.5 \times 9.8 = 350 \times \Delta x$ (1 MARK)

$\Delta x = 0.126 = 0.13$ m (1 MARK)

b $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 350 \times (0.126)^2$ (1 MARK)

$SPE = 2.8$ J (1 MARK)

10 a $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$GPE_i = SPE_f \ \therefore mgh = \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$0.50 \times 9.8 \times 1.0 = \frac{1}{2} \times k \times (0.15)^2 \ \therefore k = 4.4 \times 10^2$ N m^{-1} (1 MARK)

b By conservation of energy: $h = 1.0$ m

c $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$GPE_i = KE_f \ \therefore mgh = \frac{1}{2}mv^2$

$0.5 \times 9.8 \times 1.0 = \frac{1}{2} \times 0.5 \times v^2$ (1 MARK)

$v = 4.4$ m s^{-1} (1 MARK)

Previous lessons

11 a $F_N = \frac{mv^2}{r} - mg = 0 \ \therefore 0 = \frac{m \times v^2}{1.0} - m \times 9.8$ (1 MARK)

$v = 3.13 = 3.1$ m s^{-1} (1 MARK)

b $GPE_i + KE_i = KE_f + GPE_f$, where $KE_i = 0$

$GPE_i = KE_f + GPE_f \ \therefore mgh_i = \frac{1}{2}mv^2 + mgh_f$ (1 MARK)

$m \times 9.8 \times h = \frac{1}{2} \times m \times 3.13^2 + m \times 9.8 \times 2$ (1 MARK)

Mass cancels out

$h = 2.5$ m (1 MARK)

12 Since momentum is conserved $v_{initial\,puck} = v_{final\,puck} = 30$ m s^{-1} (1 MARK)

$KE_i = \frac{1}{2}mv^2 = \frac{1}{2} \times 1.5 \times 30^2 = 675$ J

$KE_f = \frac{1}{2}mv^2 = \frac{1}{2} \times 1.5 \times 30^2 = 675$ J

$KE_i = KE_f$, therefore the collision was elastic. (1 MARK)

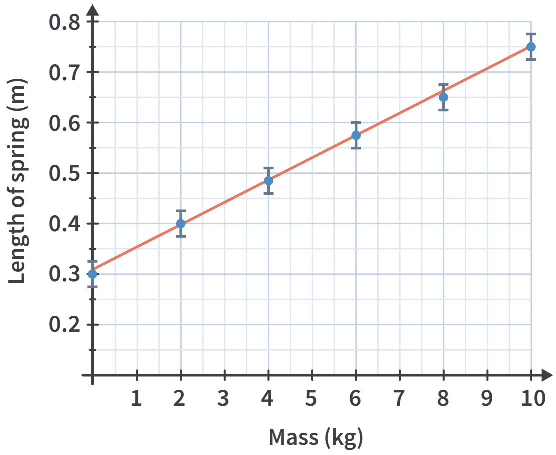
OR

Since momentum is conserved $v_{initial\,puck} = v_{final\,puck} = 30$ m s^{-1} (1 MARK)

The collision must be elastic, since two objects with the same mass and speed will have the same kinetic energy. (1 MARK)

Key science skills

13 a



- I have labelled the horizontal and vertical axes and included units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each point of data.
- I have drawn correctly sized uncertainty bars.
- I have drawn a line of best fit which passes through all uncertainty bars.

b Use two points on a line of best fit which passes through all uncertainty bars to determine rise and run.

$gradient = \frac{rise}{run} = \frac{0.75 - 0.31}{10.0 - 0} = 0.044$ m kg^{-1} (1 MARK)

$gradient = \frac{rise}{run} = \frac{\Delta x}{m}$ and $k = \frac{F}{\Delta x} = \frac{mg}{\Delta x}$ so $k = \frac{g}{gradient}$ (1 MARK)

$k = \frac{9.8}{0.044} = 2.2 \times 10^2$ N m^{-1} (1 MARK)

Depending on the line of best fit drawn, answers between 1.9×10^2 N m^{-1} and 2.5×10^2 N m^{-1} are acceptable.

3F Vertical spring-mass systems

Theory review questions

1 C **2** C **3** A **4** D

Exam-style questions

This lesson

5 [Yokabit, Valeriy, and JL have all suggested incorrect maximum heights.[1]] [The highest and lowest position are equidistant from the equilibrium position[2]] [which means the highest position must be 1.0 cm above the equilibrium position.[3]]

- I have explicitly addressed each student's suggestion.[1]
- I have used the relevant theory: equilibrium position as midpoint of oscillation.[2]
- I have explicitly addressed the correct height the mass will reach.[3]
- I have related my answer to the context of the question.

6 a $GPE_{top} = SPE_{bot}$

$mgh_{top} = \frac{1}{2}k(\Delta x_{bot})^2$ (1 MARK)

Since $h_{top} = \Delta x_{bot}$: $0.800 \times 9.8 \times \Delta x_{bot} = \frac{1}{2} \times 12 \times (\Delta x_{bot})^2$ (1 MARK)

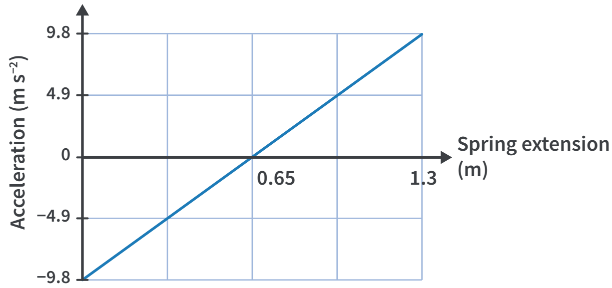
$\Delta x_{bot} = 1.3$ m (1 MARK)

b $SPE_{mid} + KE_{mid} + GPE_{mid} = SPE_{bot}$ (1 MARK)

$\frac{1}{2} \times 12 \times 0.65^2 + \frac{1}{2} \times 0.800 \times v_{mid}^2 + 0.800 \times 9.8 \times 0.65$
$= \frac{1}{2} \times 12 \times 1.3^2$ (1 MARK)

$v_{mid} = 2.5$ m s^{-1} (1 MARK)

c



- I have shown the acceleration to be −9.8 m s^{-2} when the spring is unstretched.
- I have shown the acceleration to be +9.8 m s^{-2} at maximum extension (1.3 m).
- I have shown the acceleration to change linearly between the top and bottom of the motion.
- I have labelled each axis including units and used appropriate scales.

d $\Delta x_{bot} = \Delta x_{mid} + (\Delta x_{mid} - \Delta x_{top})$

$\Delta x_{bot} = 0.65 + (0.65 - 0.30) = 1.00$ m

7 a $k = gradient = \frac{30-0}{0.25-0} = 120\ \text{N m}^{-1}$

b $\Delta SPE = SPE_Y - SPE_X$ (1 MARK)

$\Delta SPE = \frac{1}{2}k(\Delta x_Y)^2 - \frac{1}{2}k(\Delta x_X)^2$

$\Delta SPE = \frac{1}{2} \times 120 \times (0.4)^2 - \frac{1}{2} \times 120 \times (0.2)^2 = 7.2\ \text{J}$ (1 MARK)

OR

$\Delta SPE = area\ under\ the\ graph = \frac{48+24}{2} \times (0.4 - 0.2)$ (1 MARK)

$\Delta SPE = \frac{48+24}{2} \times (0.4\ 0.2) = 7.2\ \text{J}$ (1 MARK)

c $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = GPE_f + SPE_f$ (1 MARK)

$\frac{1}{2}k(\Delta x_Y)^2 = mgh + \frac{1}{2}k(\Delta x_X)^2$

$\frac{1}{2} \times 120 \times (0.40)^2 = 0.50 \times 9.8 \times h + \frac{1}{2} \times 120 \times (0.20)^2$ (1 MARK)

$h = 1.47 = 1.5\ \text{m}$ (1 MARK)

d $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = GPE_f + KE_f + SPE_f$ (1 MARK)

$\frac{1}{2}k(\Delta x_Y)^2 = mgh + \frac{1}{2}mv^2 + \frac{1}{2}k(\Delta x_X)^2$

$\frac{1}{2} \times 120 \times (0.40)^2 = 0.50 \times 9.8 \times 0.20 + \frac{1}{2} \times 0.50 \times v^2 + \frac{1}{2} \times 120 \times (0.20)^2$ (1 MARK)

$v = 5.0\ \text{m s}^{-1}$ (1 MARK)

e [The total energy of the mass-spring system remains constant.[1]] [Kinetic energy of the ball increases as the ball is launched.[2]] [Strain potential energy decreases as the ball is launched.[3]] [Gravitational potential energy increases as the ball is launched.[4]]

- I have explicitly addressed how the total energy changes.[1]
- I have explicitly addressed how kinetic energy changes.[2]
- I have explicitly addressed how strain potential energy changes.[3]
- I have explicitly addressed how gravitational potential energy changes.[4]

8 [Total energy should remain constant.[1]] [The students' mistake was to take the strain potential energy to be zero where it was released, rather than from the unstretched length (which is important since SPE is not linear – it is proportional to Δx^2).[2]] [Since the mass was released from 20 cm below its unstretched length, it would have initially had a non-zero strain potential energy.[3]]

- I have used the relevant theory: conservation of energy.[1]
- I have explicitly addressed the students mistake.[2]
- I have related my answer to the context of the question.[3]

Previous lessons

9 $v = \frac{\Delta s}{\Delta t}\ \therefore 15.3 = \frac{25}{t}\ \therefore t = 1.63\ \text{s}$

$s = ut + \frac{1}{2}at^2 = 12.9 \times 1.63 + \frac{1}{2} \times (-9.8) \times 1.63^2$ (1 MARK)

$s = 7.93\ \text{m}$ (1 MARK)

$h = 2.0 + 7.93 = 9.9\ \text{m}$ (1 MARK)

10 $v_{top} = \sqrt{rg}$

$80.0 = \sqrt{r \times 9.8}$ (1 MARK)

$r = 653\ \text{m}$ (1 MARK)

$F_{N,bot} = \frac{mv_{bot}^2}{r} + mg = \frac{60.0 \times 100^2}{653} + 60.0 \times 9.8$ (1 MARK)

$F_{N,bot} = 1.5 \times 10^3\ \text{N}$ (1 MARK)

Key science skills

11 a Uncertainty $= \frac{1}{2} \times 5.0 = 2.5\ \text{cm}$

b Independent variable: spring constant
Dependant variable: maximum extension of spring
Controlled variable: mass **OR** initial height of mass

Chapter 3 Review

Section A

1 A	**2** B	**3** B	**4** A	**5** C

Section B

6 $v = \frac{90}{3.6} = 25\ \text{m s}^{-1}$

$F_{avg}\Delta t = mv\ \therefore F_{avg} \times 0.10 = 1200 \times 25$ (1 MARK)

$F_{avg} = 3.0 \times 10^5\ \text{N}$ (1 MARK)

7 [Crumple zones make crashes safer by reducing the force of the collision.[1]] [By $I = F\Delta t$,[2]] [increasing Δt (the time of the collision) lowers the force since the impulse remains constant.[3]]

- I have explicitly addressed how crumple zones improve safety.[1]
- I have used the relevant theory: relationship between impulse and force.[2]
- I have explicitly addressed the importance of increasing the collision time.[3]

8 [The PE teacher is incorrect.[1]] [Work is given by $W = Fs$.[2]] [As the displacement (s) equals zero for stationary objects, the PE teacher is not doing work on the object.[3]]

- I have explicitly evaluated the statement.[1]
- I have used the relevant theory: work done.[2]
- I have explicitly addressed the displacement of the object.[3]

9 **a** There are 32 boxes under the graph (between 30 and 34 is acceptable) (1 MARK)

W = Area under force-displacement graph

$W = 32 \times 0.5 \times 10$ (1 MARK)

$W = 1.6 \times 10^2$ J (1 MARK)

b $KE_f - KE_i = W$

$\frac{1}{2} \times 0.150 \times v_f^2 - 0 = 1.6 \times 10^2$ (1 MARK)

$v_f = 46$ m s^{-1} (1 MARK)

10 $p_A + p_B = p_{tot}$ $\therefore m_A u_A + m_B u_B = m_{tot} v$
$400 \times 15.0 + 1200 \times 10.0 = 1600 \times v$

$v = 11.3$ m s^{-1} (1 MARK)

$KE_i = \frac{1}{2} m_A u_A{}^2 + \frac{1}{2} m_B u_B{}^2 = \frac{1}{2} \times 400 \times 15^2 + \frac{1}{2} \times 1200 \times 10^2$
$KE_i = 1.05 \times 10^5$ J (1 MARK)

$KE_f = \frac{1}{2} m_{tot} v^2 = \frac{1}{2} \times 1600 \times 11.3^2 = 1.01 \times 10^5$ J (1 MARK)

As $KE_i \neq KE_f$ the collision is inelastic (1 MARK)

11 $KE_i + GPE_i = KE_f + GPE_f$

$\therefore KE_i + GPE_i = KE_f$ (1 MARK)

$6.25 + \frac{1}{2} \times 9.8 \times h = \frac{1}{2} \times 0.50 \times 31^2$ (1 MARK)

$h = 48$ m (1 MARK)

12 **a** $SPE_f = \Delta GPE = mg\Delta h = 1.5 \times 9.8 \times 5.6$ (1 MARK)

$SPE_f = 82$ J (1 MARK)

OR

$SPE_f = \frac{1}{2} k(\Delta x)^2 = \frac{1}{2} \times 457 \times 0.6^2$ (1 MARK)

$SPE_f = 82$ J (1 MARK)

b The ball will reach its maximum speed when it stops accelerating.

$F_{net} = 0$ $\therefore mg = k\Delta x$ (1 MARK)

$1.5 \times 9.8 = 457 \times \Delta x$ (1 MARK)

$\Delta x = 3.2 \times 10^{-2}$ m (1 MARK)

c $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

$\therefore GPE_i = KE_f + SPE_f$ (1 MARK)

$1.5 \times 9.8 \times (5.00 + 7.35 \times 10^{-2}) = KE_f + \frac{1}{2} \times 200 \times (7.35 \times 10^{-2})^2$ (1 MARK)

$KE_f = 74$ J (1 MARK)

13 **a** Energy delivered to light is equivalent to $\Delta GPE = mg\Delta h = 30 \times 9.8 \times 2.0$ (1 MARK)

$GPE = 588 = 5.9 \times 10^2$ J (1 MARK)

b $P = \frac{\Delta E}{t}$ $\therefore 1.5 = \frac{588}{t}$ (1 MARK)

$t = 3.9 \times 10^2$ s (1 MARK)

14 **a** $v = 240$ km h^{-1} $= \frac{240}{3.6} = 66.7$ m s^{-1}

$GPE_i + KE_i = GPE_f + KE_f + E_{dis}$

$\therefore GPE_i = GPE_f + KE_f + E_{dis}$ (1 MARK)

$70.0 \times 9.8 \times 7661 = 70.0 \times 9.8 \times 61 + \frac{1}{2} \times 70.0 \times 66.7^2 + E_{dis}$ (1 MARK)

$E_{dis} = 5.1 \times 10^6$ J (1 MARK)

b Total energy at the bottom must equal the total energy when Aikins first touches the net.

$KE_{bot} + GPE_{bot} + SPE_{bot} = KE_{top} + GPE_{top} + SPE_{top}$

$\therefore SPE_{bot} = KE_{top} + GPE_{top}$ (1 MARK)

$\frac{1}{2} \times k \times 61^2 = \frac{1}{2} \times 70.0 \times 66.7^2 + 70.0 \times 9.8 \times 61$ (1 MARK)

$k = 1.1 \times 10^2$ N m^{-1} (1 MARK)

c $I = \Delta p = mu - mv$

$I = 70.0 \times 66.7 - 70.0 \times 0$ (1 MARK)

$I = 4.67 \times 10^3$ N s or kg m s^{-1} (1 MARK)

15 **a** [As the mass descends from the top to the bottom the GPE decreases,[1]][the SPE increases,[2]][and the KE increases until the middle point[3]][and then decreases back to zero at the bottom.[4]][The total energy of the system remains constant[5]][due to energy conservation.[6]]

- I have explicitly addressed the variation in GPE.[1]
- I have explicitly addressed the variation in SPE.[2]
- I have explicitly addressed the variation in KE from top to middle.[3]
- I have explicitly addressed the variation in KE from middle to bottom.[4]
- I have explicitly addressed the total energy of the system.[5]
- I have used the relevant theory: conservation of energy.[6]

b $GPE_{top} + SPE_{top} = GPE_{bot} + SPE_{bot}$

$\therefore GPE_{top} = SPE_{bot}$

$4.8 \times 9.8 \times h = \frac{1}{2} \times 50 \times (\Delta x)^2$ (1 MARK)

$h = \Delta x$ $\therefore 4.8 \times 9.8 = \frac{1}{2} \times 50 \times \Delta x$ (1 MARK)

$\Delta x = 1.9$ m (1 MARK)

4A Special relativity concepts

Theory review questions

1 B
2 C
3 C
4 D

5 **S1** both

S2 classical physics

S3 special relativity

S4 both

S5 special relativity

Exam-style questions

This lesson

6 B. This frame is not inertial because it is changing direction. Note that we treat the surface of the Earth as an inertial reference frame for the purposes of VCE Physics.

7 C. All observers measure the same speed of light in a vacuum.

8 [Anna is not correct.[1]] [An object can accelerate while moving at a constant speed by changing its direction, such as in circular motion.[2]] [Any object that is accelerating is not in an inertial frame of reference.[3]]

- I have explicitly addressed if Anna is correct.[1]
- I have used the relevant theory: acceleration as a change in direction.[2]
- I have used the relevant theory: inertial frames of reference.[3]

9 **a** D. The speed of light is the same, regardless of the motion of the source.

b $v = \frac{\Delta s}{\Delta t}$ $\therefore 3.0 \times 10^8 = \frac{6.0 \times 10^{11}}{\Delta t}$ (1 MARK)

$\Delta t = 2.0 \times 10^3$ s (1 MARK)

Previous lessons

10 **a** Take upwards as positive. $u_y = 30 \times \sin(20°) = 10.3 = 10$ m s^{-1}

b Take upwards as positive. Vertical velocity is zero at maximum height.

$v^2 = u^2 + 2as$ $\therefore 0^2 = 10.3^2 + 2 \times (-9.8) \times s$ (1 MARK)

$s = 5.4$ m (1 MARK)

c Take upwards as positive. Ball returns to ground when displacement is zero.

$s = ut + \frac{1}{2}at^2$ $\therefore 0 = 10.3 \times t + \frac{1}{2} \times (-9.8) \times t^2$ (1 MARK)

$t = 2.1$ s (the solution $t = 0$ relates to the ball leaving the ground) (1 MARK)

11 **a** Kinetic energy is a maximum at the bottom of the ramp, before colliding with the crash mat.

$GPE_{bot} + KE_{bot} = GPE_{top} + KE_{top}$

$KE_{bot} = GPE_{top}$ $\therefore \frac{1}{2}mv^2 = mgh_{top}$

$\frac{1}{2} \times 67 \times v^2 = 67 \times 9.8 \times 13$ (1 MARK)

$v = 16$ m s^{-1} (1 MARK)

b Compression is a maximum when skateboarder has (momentarily) come to rest at the end of the ramp.

$GPE_{end} + KE_{end} + SPE_{end} = GPE_{top} + KE_{top} + SPE_{top}$

$SPE_{end} = GPE_{top}$ $\therefore \frac{1}{2}k(\Delta x)^2 = mgh_{top}$

$\frac{1}{2} \times 500 \times (\Delta x)^2 = 67 \times 9.8 \times 13$ (1 MARK)

$\Delta x = 5.8$ m (1 MARK)

Key science skills

12 [Emma's experiment is not valid. It does not measure what it claims to be measuring[1]] [because the experiment is not conducted in an inertial frame of reference due to the train changing direction.[2]] [This means the ball will travel further than 10 metres between the start and finish line (as it will take a curved path in the train's reference frame).[3]]

- I have explicitly addressed if Emma's experiment is valid.[1]
- I have used the relevant theory: inertial frames of reference.[2]
- I have related my answer to the context of the question.[3]

4B Length contraction and time dilation

Theory review questions

1 D
2 D
3 C
4 A
5 C
6 A

7 Sad Bunny, Playful Owl

8 Lucy, Mia

9 Lucy, Mia

10 Sad Bunny, Playful Owl

11 B

Exam-style questions

This lesson

12 D

13 $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(2.786 \times 10^8)^2}{(3.0 \times 10^8)^2}}}$ (1 MARK)

$\gamma = 2.7$ (1 MARK)

14 $L = \frac{L_0}{\gamma}$ and $L = \frac{L_0}{4}$ $\therefore \gamma = 4$ (1 MARK)

$v = c\sqrt{1 - \frac{1}{\gamma^2}} = 3.0 \times 10^8 \times \sqrt{1 - \frac{1}{4^2}}$ (1 MARK)

$v = 2.9 \times 10^8$ m s^{-1} (1 MARK)

15 $t = \frac{1}{5} \times 24 = 4.8$ hours, $t = t_0\gamma$ $\therefore 4.8 = t_0 \times 1.598$ (1 MARK)

$t_0 = 3.0$ hours (1 MARK)

16 $t = t_0\gamma$ $\therefore t = t_0\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ $\therefore 5.72 = 5.00 \times \frac{1}{\sqrt{1 - \frac{v^2}{(3.0 \times 10^8)^2}}}$ (1 MARK)

$v = 1.5 \times 10^8$ m s^{-1} (1 MARK)

17 B. The relative speed between the neutrino and the rocket is the only speed that is relevant to this question.

18 a $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.99c)^2}{c^2}}} = \frac{1}{\sqrt{1-0.99^2}} = 7.09$ (1 MARK)

$L = \frac{L_0}{\gamma} = \frac{10\times10^3}{7.09}$ (1 MARK)

$L = 1.4 \times 10^3$ m (1 MARK)

b $t = t_0\gamma = 2.4 \times 10^{-6} \times 7.09$ (1 MARK)

$t = 1.7 \times 10^{-5}$ s (1 MARK)

c [From the Earth's frame of reference[1]][time dilation as a result of special relativity[2]][means the muons have a longer life.[3]][As such, the muons will travel further than expected by classical physics before decaying and so more muons will reach the surface.[4]]

OR

[From the muon's frame of reference[1]][length contraction as a result of special relativity[2]][means the distance to the surface is reduced.[3]][As such, more muons than expected by classical physics can travel the distance to the surface before decaying.[4]]

- I have explicitly addressed the frame of reference.[1]
- I have used the relevant theory: time dilation OR length contraction.[2]
- I have explicitly addressed the effect of special relativity in the chosen reference frame.[3]
- I have explicitly addressed the question.[4]

19 Note this question does not require any time dilation to be calculated as all the values are measured and calculated in the same frame of reference.

$v = \frac{\Delta s}{\Delta t}$ $\therefore 0.9967 \times 3.0 \times 10^8 = \frac{1.42\times10^{-2}}{t}$ (1 MARK)

$t = 4.7 \times 10^{-11}$ s (1 MARK)

Previous lessons

20 a $s = ut + \frac{1}{2}at^2$ $\therefore 26 - 10 = 0 \times t + \frac{1}{2} \times 9.8 \times t^2$ (1 MARK)

$t = 1.81$ s $= 1.8$ s (1 MARK)

b $v = \frac{\Delta s}{\Delta t}$ $\therefore 17 = \frac{\Delta s}{1.81}$

$\Delta s = 31$ m (1 MARK)

The distance jumped (31 m) is greater than the distance to the building (20 m). Therefore, Jim will make the jump. (1 MARK)

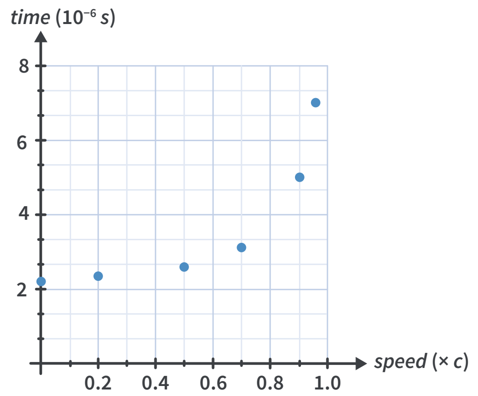
21 $mg = k\Delta x$

$m \times 9.8 = 289 \times 3.20$ (1 MARK)

$m = 94$ kg (1 MARK)

Key science skills

22



- I have identified the independent variable (speed) and dependent variable (time to decay).
- I have drawn the horizontal axis as the independent variable, and included correct units.
- I have drawn the vertical axis as the dependent variable, and included correct units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each data point.

4C Mass-energy

Theory review questions

1 B **2** B **3** B **4** A

Exam-style questions

This lesson

5 [A particle with mass cannot be accelerated to the speed of light[1]][because the kinetic energy it needs approaches infinity as its speed approaches the speed of light.[2]]

- I have explicitly addressed if a particle with mass can be accelerated to the speed of light.[1]
- I have used the relevant theory: relativistic kinetic energy.[2]

6 A. Note that option D is incorrect since the current VCE Physics Study Design considers mass as a constant quantity regardless of speed.

7 $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.8c)^2}{c^2}}} = 1.67$ (1 MARK)

$E_{tot} = \gamma mc^2 = 1.67 \times 1.67 \times 10^{-27} \times (3.0\times10^8)^2$

$E_{tot} = 2.5 \times 10^{-10}$ J (1 MARK)

8 $\Delta E = \Delta mc^2$ $\therefore 4.20 \times 10^{26} = \Delta m \times (3.0\times10^8)^2$ (1 MARK)

$\Delta m = 4.7 \times 10^9$ kg s^{-1} (1 MARK)

9 C. When energy is emitted, mass decreases according to $\Delta m = \frac{\Delta E}{c^2} = \frac{2.7\times10^{-12}}{(3.0\times10^8)^2} = 3.0 \times 10^{-29}$ kg.

10 Initial energy:

$KE_i = (\gamma_i - 1)mc^2 = (1.40-1)\times2.34\times10^{-27}\times(3.0\times10^8)^2$

$KE_i = 8.42\times10^{-11}$ J (1 MARK)

Final energy:

$KE_f = (\gamma_f - 1)mc^2 = (2.30-1)\times2.34\times10^{-27}\times(3.0\times10^8)^2$

$KE_f = 2.74\times10^{-10}$ J (1 MARK)

$W = \Delta KE = 2.74 \times 10^{-10} - 8.42 \times 10^{-11} = 1.90 \times 10^{-10}$ J (1 MARK)

OR

$W = \Delta E = (\gamma_f - \gamma_i)mc^2$ (1 MARK)

$W = (2.30-1.40)\times2.34\times10^{-27}\times(3.0\times10^8)^2$ (1 MARK)

$W = 1.90 \times 10^{-10}$ J (1 MARK)

11 $KE = (\gamma - 1)mc^2$

$1.8 \times 10^{-10} = (\gamma - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$\gamma = 2.20$ (1 MARK)

$\gamma = 2.20 = \dfrac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ $\therefore v = 2.7 \times 10^8 \text{ m s}^{-1}$ (1 MARK)

12 Classical *KE*:

$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 3.34 \times 10^{-27} \times (0.8 \times 3.0 \times 10^8)^2 = 9.6 \times 10^{-11}$ (1 MARK)

Relativistic *KE*: $\gamma = \dfrac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \dfrac{1}{\sqrt{1 - \frac{(0.8 \times 3.0 \times 10^8)^2}{(3.0 \times 10^8)^2}}} = 1.67$ (1 MARK)

$KE = (\gamma - 1)mc^2 = (1.67 - 1) \times 3.34 \times 10^{-27} \times (3.0 \times 10^8)^2 = 2.0 \times 10^{-10} \text{ J}$ (1 MARK)

Difference: $2.0 \times 10^{-10} - 9.6 \times 10^{-11} = 1.0 \times 10^{-10} \text{ J}$ (1 MARK)

13 $KE = (\gamma - 1)mc^2$ $\therefore (\gamma - 1)mc^2 = 12mc^2$ (1 MARK)

$\gamma = 13$ (1 MARK)

Previous lessons

14 $2.8 \times 10^4 \text{ km h}^{-1} = 2.8 \times 10^4 \div 3.6 \text{ m s}^{-1} = 7.78 \times 10^3 \text{ m s}^{-1}$

$p = mv = 3.0 \times 10^8 \times 7.78 \times 10^3$ (1 MARK)

$p = 2.3 \times 10^{12} \text{ kg m s}^{-1}$ (1 MARK)

15 Because $v = 0 \text{ m s}^{-1}$ at point C, we know the spring is oscillating between points A and C. Therefore $KE = 0$ J at points A and C.

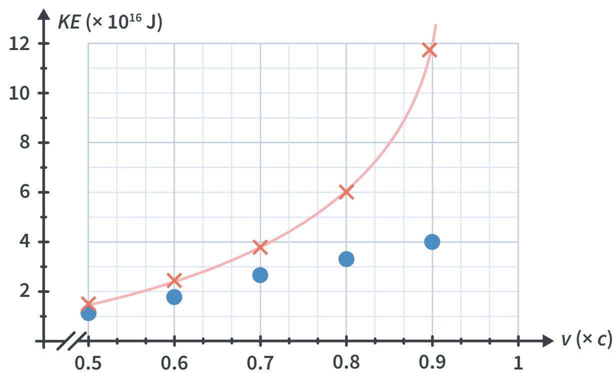
At point A and C: $SPE = \frac{1}{2}k\Delta x^2 = \frac{1}{2} \times 100 \times 2^2 = 2 \times 10^2 \text{ J}$ (1 MARK)

Due to conservation of energy, at the unstretched position where $SPE = 0$ J all 2×10^2 J from point A or C must have been converted to kinetic energy. Therefore, $KE = 2 \times 10^2$ J at point B.

Point	KE (J)	SPE (J)	
A	0	2×10^2	(1 MARK)
B	2×10^2	0	(1 MARK)
C	0	2×10^2	(1 MARK)

Key science skills

16 a



I have plotted each data point correctly.

I have drawn a curve of best fit.

b The difference between classical and relativistic kinetic energy increases as speeds approach *c*.

Chapter 4 Review

Section A

1 D **2** B **3** A **4** B **5** C

Section B

6 a Measuring distance and time in the Earth's reference frame:

$v = \dfrac{\Delta s}{\Delta t} = \dfrac{L_0}{t}$ $\therefore 0.85 \times 3.0 \times 10^8 = \dfrac{5.84 \times 10^{16}}{t}$ (1 MARK)

$t = 2.29 \times 10^8 = 2.3 \times 10^8 \text{ s}$ (1 MARK)

b $\gamma = \dfrac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \dfrac{1}{\sqrt{1 - \frac{(0.85c)^2}{c^2}}} = \dfrac{1}{\sqrt{1 - 0.85^2}} = 1.90$ (1 MARK)

$t = t_0\gamma$ $\therefore 2.29 \times 10^8 = t_0 \times 1.90$ (1 MARK)

$t_0 = 1.2 \times 10^8 \text{ s}$ (1 MARK)

c $\gamma = 1.90$ as calculated in part **b**.

$L = \dfrac{L_0}{\gamma} = \dfrac{5.84 \times 10^{16}}{1.90}$ (1 MARK)

$L = 3.1 \times 10^{16} \text{ m}$ (1 MARK)

OR

Measuring distance and time in the Earth's reference frame:

$v = \dfrac{\Delta s}{\Delta t} = \dfrac{L}{t_0}$ $\therefore 0.85 \times 3.0 \times 10^8 = \dfrac{L}{1.2 \times 10^8}$ (1 MARK)

$L = 3.1 \times 10^{16} \text{ m}$ (1 MARK)

7 $\gamma = 5$ (1 MARK)

$KE = (\gamma - 1)mc^2 = (5 - 1) \times 8000 \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 2.9 \times 10^{21} \text{ J}$ (1 MARK)

8 a $v = \dfrac{\Delta s}{\Delta t} = \dfrac{4.24 \text{ years} \times c}{20.0 \text{ years}} = 0.212c$

b $\gamma = \dfrac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \dfrac{1}{\sqrt{1 - \frac{(0.212c)^2}{c^2}}} = \dfrac{1}{\sqrt{1 - 0.212^2}} = 1.0233$ (1 MARK)

$t = t_0\gamma$ $\therefore 20.0 = t_0 \times 1.0233$ (1 MARK)

$t_0 = 19.5 \text{ years}$ (1 MARK)

c $\gamma = 1.0233$ as calculated in part **b**.

$L = \dfrac{L_0}{\gamma} = \dfrac{4.24}{1.0233}$ (1 MARK)

$L = 4.14$ light-years (1 MARK)

OR

Measuring distance and time in the spacecraft's reference frame:

$v = \dfrac{\Delta s}{\Delta t} = \dfrac{L}{t_0}$ $\therefore 0.212c = \dfrac{L}{19.5 \text{ years}}$ (1 MARK)

$L = 0.212c \times 19.54 \text{ years} = 4.14$ light-years (1 MARK)

9 [The protons are not in an inertial frame of reference when speeding up[1]][nor when travelling at a constant speed.[2]][In both cases, the protons are accelerating (even when travelling at a constant speed they undergo centripetal acceleration) which means their reference frame is non-inertial.[3]]

- I have explicitly addressed the reference frame when speeding up.[1]
- I have explicitly addressed the reference frame when travelling at a constant speed.[2]
- I have used the relevant theory: conditions for inertial frames of reference.[3]
- I have related my answer to the context of the question.

10 [From the Earth's frame of reference[1]][time dilation as a result of special relativity[2]][means the muons have a longer life.[3]][As such, the muons will travel further than expected by classical physics before decaying and so more muons will reach the surface.[4]]

OR

[From the muon's frame of reference[1]][length contraction as a result of special relativity[2]][means the distance to the surface is reduced.[3]][As such, more muons than expected by classical physics can travel the distance to the surface before decaying.[4]]

- I have explicitly addressed the frame of reference.[1]
- I have used the relevant theory: time dilation **OR** length contraction.[2]
- I have explicitly addressed the effect of special relativity in the chosen reference frame.[3]
- I have explicitly addressed the answer.[4]

11 **a** 12 742 km

Length contraction occurs only in the direction of the particle's motion.

b The particle will measure a contracted depth of the Earth, L.

$L = \frac{L_0}{\gamma} = \frac{12742 \times 10^3}{3.2 \times 10^{11}}$ (1 MARK)

$L = 4.0 \times 10^{-5}$ m (1 MARK)

c $KE = (\gamma - 1)mc^2$

$KE = (3.2 \times 10^{11} - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 48$ J (1 MARK)

d 0 J

The particle is not moving relative to its own reference frame.

12 **a** $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(0.8c)^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.8^2}} = 1.667$ (1 MARK)

$E_{total} = \gamma mc^2 = 1.667 \times 530 \times 10^3 \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{total} = 8.0 \times 10^{22}$ J (1 MARK)

b Equate the relativistic KE of the rocket with the rest energy of the fuel.

$(\gamma - 1)m_{rocket}c^2 = m_{fuel}c^2$ (1 MARK)

$\gamma = 1.667$ as calculated in part **a**.

$(1.667 - 1) \times 530 \times 10^3 \times (3.0 \times 10^8)^2 = m_{fuel}(3.0 \times 10^8)^2$ (1 MARK)

$m_{fuel} = 3.5 \times 10^5$ kg (1 MARK)

13 [Energy is produced in the Sun by nuclear fusion which is when two or more nuclei combine to form one or more nuclei.[1]][The total mass before the reaction is greater than the total mass after the reaction,[2]][and the mass defect (lost) is converted into electromagnetic radiation.[3]]

- I have explicitly addressed the process by which nuclear fusion occurs.[1]
- I have explicitly addressed a decrease in mass in a fusion reaction.[2]
- I have used the relevant theory: mass-energy equivalence.[3]

14 $\Delta m = m_i - m_f = (6.647 \times 10^{-27} + 1.9926 \times 10^{-26}) - 2.6563 \times 10^{-26}$

$\Delta m = 1.0 \times 10^{-29}$ kg (1 MARK)

$\Delta E = \Delta mc^2 = 1.0 \times 10^{-29} \times (3.0 \times 10^8)^2 = 9.0 \times 10^{-13}$ J (1 MARK)

15 [Objects with mass can never reach the speed of light[1]][because the amount of additional energy required to increase the object's speed increases with the Lorentz factor, which approaches infinity as the speed approaches the speed of light.[2]][Since $KE = (\gamma - 1)mc^2$, an infinite amount of energy would be required to reach the speed of light.[3]]

- I have explicitly addressed the speed limit of an object with mass.[1]
- I have explicitly addressed the Lorentz factor.[2]
- I have used the relevant theory: relativistic kinetic energy.[3]

16 Mass-energy is conserved.

$E_{deuterium} + E_{deuterium} = E_{tritium} + E_{proton} + E_{radiation}$ (1 MARK)

$2 \times m_{deuterium}c^2 = m_{tritium}c^2 + m_{proton}c^2 + E_{radiation}$

$2 \times m_{deuterium} \times (3.0 \times 10^8)^2$
$= 5.01 \times 10^{-27} \times (3.0 \times 10^8)^2 + 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2 + 6.45 \times 10^{-13}$
(1 MARK)

$m_{deuterium} = 3.34 \times 10^{-27}$ kg (1 MARK)

Unit 3, AOS 3 Review

Section A

1 B **2** D **3** A **4** C **5** B

Section B

6 $F_{on\ A\ by\ B} = m_A g = 30 \times 9.8 = 2.9 \times 10^2$ N upwards (2 MARKS)

7 **a** $F_{g1} = m_1 g = 9.8 \times 0.500 = 4.90 = 4.9$ N (1 MARK)

$F_{g2} = m_2 g = 9.8 \times 0.300 = 2.94 = 2.9$ N (1 MARK)

b $F_{net} = F_{g1} - F_{g2} = m_{tot}a$

$4.90 - 2.94 = (0.500 + 0.300) \times a$ (1 MARK)

$a = 2.45 = 2.5$ m s^{-2} (1 MARK)

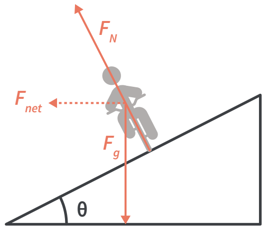
c Consider m_2

$F_{net} = m_2 a$

$T - 2.94 = 0.300 \times 2.45$ (1 MARK)

$T = 3.7$ N (1 MARK)

8 a



I have drawn the normal force vector perpendicular to the slope of the track from the track surface.

I have drawn the force due to gravity vector straight down from the centre of the cyclist.

I have drawn the net force vector with a dashed arrow pointing horizontally to the left.

I have drawn the size of the force due to gravity and normal force vectors so that their vector sum is horizontal (consistent with the net force vector).

b $v = \sqrt{rg\tan(\theta)} = \sqrt{30 \times 9.8 \times \tan(37.4°)}$ (1 MARK)

$v = 15$ m s^{-1} (1 MARK)

c $F_{net} = \frac{mv^2}{r} = \frac{120 \times 15^2}{30}$ (1 MARK)

$F_{net} = 9.0 \times 10^2$ N (1 MARK)

9 a $v = \sqrt{gr} = \sqrt{9.8 \times 0.50}$ (1 MARK)

$v = 2.2$ m s^{-1} (1 MARK)

6.0 m s^{-1} > 2.2 m s^{-1} therefore the string will remain under tension (1 MARK)

b $KE_{top} + GPE_{top} = KE_{bot} + GPE_{bot}$ (1 MARK)

$\frac{1}{2}mu^2 + mgh = \frac{1}{2}mv^2 + 0$

$\frac{1}{2} \times 1.5 \times 6.0^2 + 1.5 \times 9.8 \times 1.0 = \frac{1}{2} \times 1.5 \times v^2$ (1 MARK)

$v = 7.5$ m s^{-1} (1 MARK)

10 Kinetic energy is at a maximum just before the cannonball hits the ground.

$KE_f = KE_i + GPE_i$ (1 MARK)

$KE_f = \frac{1}{2}mu^2 + mgh = \frac{1}{2} \times 2.0 \times 10^3 \times 720^2 + 2.0 \times 10^3 \times 9.8 \times 530$ (1 MARK)

$KE_f = 5.3 \times 10^8$ J (1 MARK)

11 [The gravitational potential energy is maximum at the top and decreases as the mass falls.[1]][The spring potential energy is a minimum at the top and increases as the mass falls.[2]][The kinetic energy is zero at the top and increases to a maximum in the middle before decreasing to zero at the bottom.[3]][The total energy of the mass (gravitational potential and kinetic) decreases as the mass falls.[4]]

I have explicitly addressed how the gravitational potential energy varies as the mass falls.[1]

I have explicitly addressed how the strain potential energy varies as the mass falls.[2]

I have explicitly addressed how the kinetic energy varies as the mass falls.[3]

I have explicitly addressed how the total energy **of the mass** varies as the mass falls.[4]

12 a Due to conservation of momentum:

$p_i = p_f \therefore m_{club}u_{club} + m_{ball}u_{ball} = m_{club}v_{club} + m_{ball}v_{ball}$ (1 MARK)

$0.330 \times 70 + 0.045 \times 0 = 0.330 \times 60 + 0.045 \times v_{ball}$

$v_{ball} = 73$ m s^{-1} (1 MARK)

b $KE_i = \frac{1}{2}m_{club}u_{club}^2 + \frac{1}{2}m_{ball}u_{ball}^2$

$KE_i = \frac{1}{2} \times 0.330 \times 70^2 + 0 = 8.1 \times 10^2$ J (1 MARK)

$KE_f = \frac{1}{2}m_{club}v_{club}^2 + \frac{1}{2}m_{ball}v_{ball}^2$

$KE_f = \frac{1}{2} \times 0.330 \times 60^2 + \frac{1}{2} \times 0.045 \times 73^2 = 7.1 \times 10^2$ J (1 MARK)

$KE_i \neq KE_f$ therefore the collision was not elastic. (1 MARK)

13 $v = \frac{\Delta s}{\Delta t} \therefore 3.0 \times 10^8 = \frac{6.0 \times 10^9}{\Delta t}$ (1 MARK)

$\Delta t = 20$ s (1 MARK)

14 $L = \frac{L_0}{\gamma} \therefore \frac{1}{5} = \frac{1}{\gamma} \therefore \gamma = 5$

$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \therefore 5 = \frac{1}{\sqrt{1 - \frac{v^2}{(3.0 \times 10^8)^2}}}$ (1 MARK)

$v = 2.9 \times 10^8$ m s^{-1} (1 MARK)

15 a The spring constant is the gradient of the force displacement graph so:

$k = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{200 - 0}{0.40 - 0}$ (1 MARK)

$k = 5.0 \times 10^2$ N m^{-1} (1 MARK)

b $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 5.0 \times 10^2 \times 0.40^2$ (1 MARK)

$SPE = 40$ J (1 MARK)

c $SPE_i = GPE_f = mgh \therefore 40 = 0.40 \times 9.8 \times (h + 0.40)$ (1 MARK)

$h = 9.8$ m (1 MARK)

16 2.68×10^5 km s^{-1} = 2.68×10^8 m s^{-1}

$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(2.68 \times 10^8)^2}{(3.0 \times 10^8)^2}}} = 2.23$ (1 MARK)

$KE = (\gamma - 1)mc^2 = (2.23 - 1) \times 4.9 \times 10^5 \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 5.4 \times 10^{22}$ J (1 MARK)

REVIEW

5A Gravitational fields and forces

Theory review questions

1 B **2** C **3** D **4** C

5 Earth's mass

6 Astronaut's mass

7 Both Earth's mass and astronaut's mass

Exam-style questions

This lesson

8 C

9 a $F = G\dfrac{M_1 M_2}{r^2} = 6.67 \times 10^{-11} \times \dfrac{480 \times 5.98 \times 10^{24}}{(7.00 \times 10^6)^2}$ (1 MARK)

$F = 3.91 \times 10^3$ N (1 MARK)

b Acceleration of the spacecraft due to Earth's gravity is equivalent to the Earth's gravitational field strength.

$g = G\dfrac{M}{r^2} = 6.67 \times 10^{-11} \times \dfrac{5.98 \times 10^{24}}{(7.00 \times 10^6)^2}$ (1 MARK)

$g = 8.14$ m s^{-2} or N kg^{-1} (1 MARK)

OR

$F = mg \;\therefore\; 3.907 \times 10^3 = 480 \times g$ (1 MARK)

$g = 8.14$ m s^{-2} or N kg^{-1} (1 MARK)

10 [Bob is incorrect.[1]][The gravitational field strength is not zero outside a planet's atmosphere.[2]][Astronauts appear to have a 'zero gravity experience' because[3]][there is no normal force acting on them as they are in constant free fall around Earth with the spacecraft falling at the same rate.[4]]

- I have explicitly addressed whether or not Bob is correct.[1]
- I have used the relevant theory: gravitational fields.[2]
- I have explicitly addressed the 'zero gravity experience'.[3]
- I have used the relevant theory: zero normal force.[4]

11 $F = G\dfrac{M_1 M_2}{r^2} \;\therefore\; 50 = 6.67 \times 10^{-11} \times \dfrac{250 \times M}{(4.0 \times 10^6)^2}$ (1 MARK)

$M = 4.8 \times 10^{22}$ kg (1 MARK)

12 a Increased. Gravitational field strength decreases as distance from object increases.

b $g_2 = \dfrac{g_1}{n^2} \;\therefore\; 0.089 = \dfrac{0.80}{n^2}$ (1 MARK)

$n^2 = 9.0 \;\therefore\; n = 3$

Mariner 10 moved three times further away from the centre of Mercury. (1 MARK)

13 a Acceleration of the probe due to Mars' gravity is equivalent to Mars' gravitational field strength.

$g = G\dfrac{M}{r^2} = 6.67 \times 10^{-11} \times \dfrac{6.39 \times 10^{23}}{(3.39 \times 10^6 + 3.0 \times 10^5)^2}$ (1 MARK)

$g = 3.130 = 3.13$ m s^{-2} or N kg^{-1} (1 MARK)

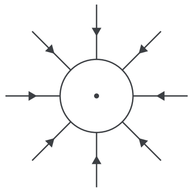
b $F = mg$

Use $g = 3.130$ N kg^{-1} from part **a**.

$F = 1.12 \times 10^3 \times 3.130$ (1 MARK)

$F = 3.51 \times 10^3$ N (1 MARK)

c



d $F = G\dfrac{M_1 M_2}{r^2} = 6.67 \times 10^{-11} \times \dfrac{6.39 \times 10^{23} \times 80}{(3.39 \times 10^6)^2}$ (1 MARK)

$F = 3.0 \times 10^2$ N (1 MARK)

Previous lessons

14 a Take right as positive and left as negative.

$p_i = m_B u_B + m_S u_S = 15\,000 \times 8.3 + 340 \times 56$ (1 MARK)

$p_i = 1.44 \times 10^5$ kg m s^{-1}

$p_i = p_f = m_B v_B + m_S v_S \;\therefore\; 1.44 \times 10^5 = 15\,000 \times v_B + 340 \times (-5)$ (1 MARK)

$v_B = 9.7$ m s^{-1} to the right (1 MARK)

b $KE_i = \frac{1}{2}m_B u_B{}^2 + \frac{1}{2}m_S u_S{}^2 = \frac{1}{2} \times 15\,000 \times 8.3^2 + \frac{1}{2} \times 340 \times 56^2$

$KE_i = 1.0 \times 10^6$ J (1 MARK)

$KE_f = \frac{1}{2}m_B v_B{}^2 + \frac{1}{2}m_S v_S{}^2 = \frac{1}{2} \times 15\,000 \times 9.7^2 + \frac{1}{2} \times 340 \times (-5)^2$

$KE_f = 7.1 \times 10^5$ J (1 MARK)

Kinetic energy was lost in the collision as $KE_i > KE_f$. Therefore the collision was inelastic. (1 MARK)

15 $KE = (\gamma - 1)mc^2$

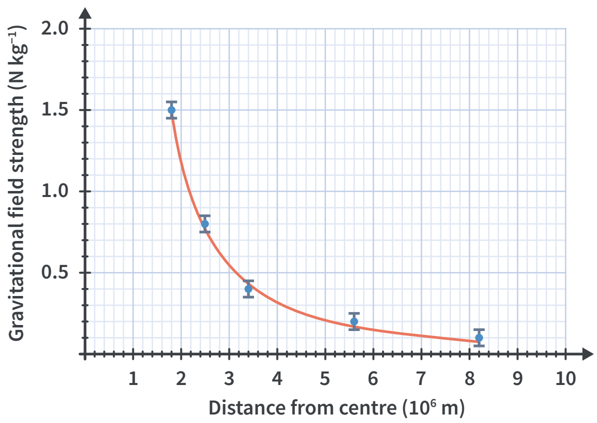
$5.434 \times 10^{20} = (\gamma - 1) \times 1500 \times (3.0 \times 10^8)^2$ (1 MARK)

$\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}} = 5.03$ (1 MARK)

$v = 2.9 \times 10^8$ m s^{-1} (1 MARK)

Key science skills

16 a



- 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 axes so that the data takes up more than half of each axis.
- I have plotted each data point.
- I have drawn correctly sized uncertainty bars.
- I have drawn a smooth curve of best fit which passes through all uncertainty bars.

b Maximum mass of Moon will be calculated using the maximum possible gravitational field strength. ∴ when $r = 1.80 \times 10^3$ km, $g = 1.55$ N kg^{-1} (1 MARK)

$g = G\frac{M}{r^2}$ ∴ $1.55 = 6.67 \times 10^{-11} \times \frac{M}{(1.80 \times 10^6)^2}$ (1 MARK)

$M = 7.53 \times 10^{22}$ kg (1 MARK)

5B Gravitational potential energy in non-uniform fields

Theory review questions

1 D	**2** C	**3** D	**4** B
5 A	**6** C	**7** C	

Exam-style questions

This lesson

8 a There are approximately 15 squares (between 14 and 16 is acceptable)

Area of each square = $(2.0 \times 10^7 \text{ m}) \times (2.0 \times 10^3 \text{ N}) = 4.0 \times 10^{10}$ J (1 MARK)

$W = 15 \times 4.0 \times 10^{10}$ (1 MARK)

$W = 6.0 \times 10^{11}$ J (1 MARK)

b [As distance from the centre of Saturn decreases, the gravitational potential energy of an object also decreases.[1]][Therefore the gravitational potential energy of Cassini would decrease.[2]]

- I have used the relevant theory: gravitational potential energy in non-uniform fields.[1]
- I have explicitly addressed the change in Cassini's gravitational potential energy.[2]

c Using the graph we can see that at 8.0×10^7 m from the centre of Saturn, Casini experiences a force of approximately 15×10^3 N.

$F_g = mg$ ∴ $15 \times 10^3 = 5700 \times g$ (1 MARK)

$g = 2.6$ m s^{-2} (1 MARK)

9 a There are approximately 7 squares (between 6 and 7 is acceptable)

Area of each square = $(1.0 \text{ N kg}^{-1}) \times (1.0 \times 10^9 \text{ m}) = 1.0 \times 10^9$ J kg^{-1} (1 MARK)

$\Delta GPE = 7 \times 1.0 \times 10^9 \times 555$ (1 MARK)

$\Delta GPE = 3.9 \times 10^{12}$ J (1 MARK)

b When distance from the Sun is 8.0×10^9 m, gravitational field strength is approximately 2.0 N kg^{-1}

$F_g = mg = 555 \times 2.0$ (1 MARK)

$F_g = 1.1 \times 10^3$ N (1 MARK)

10 a There are approximately 28 squares (between 26 and 30 is acceptable)

Area of each square = $(2.00 \times 10^5 \text{ m}) \times (0.0200 \text{ N kg}^{-1})$
$= 4.00 \times 10^3$ J kg^{-1} (1 MARK)

$\Delta KE = 28 \times 4.00 \times 10^3 \times 500 = 5.60 \times 10^7$ J (1 MARK)

$\Delta KE = 5.60 \times 10^7$ J (1 MARK)

b $\Delta KE = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$5.60 \times 10^7 = \frac{1}{2} \times 500 \times v^2 - \frac{1}{2} \times 500 \times 50^2$ (1 MARK)

$v = 476$ m s^{-1} (between 459 and 492 m s^{-1} is acceptable, dependent on part **a**.) (1 MARK)

Previous lessons

11 a $W = \Delta GPE = mg\Delta h = 252 \times 1.214 \times (10 - 0)$ (1 MARK)

$W = 3.06 \times 10^3$ J (1 MARK)

b $KE_i + GPE_i = KE_f + GPE_f$

$KE_f = mg\,h_i = 252 \times 1.214 \times 5.00$ (1 MARK)

$KE = 1.53 \times 10^3$ J (1 MARK)

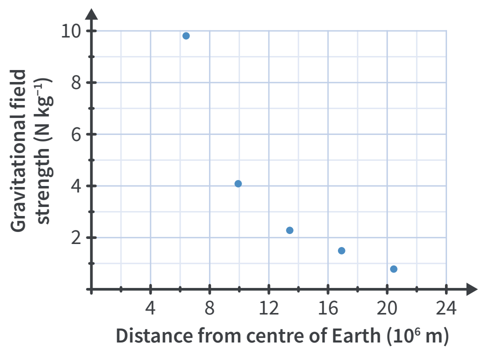
12 $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{0.95^2}{1^2}}} = 3.20$ (1 MARK)

$E_{tot} = \gamma mc^2 = 3.20 \times 10\,000 \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{tot} = 2.9 \times 10^{21}$ J (1 MARK)

Key science skills

13 a



- 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 axes so that the data takes up more than half of each axis.
- I have plotted each data point.

b [Kat's results are more accurate[1]][because they were consistently closer than Al's data to the true values.[2]]

- I have explicitly addressed which results were more accurate.[1]
- I have used the relevant theory: accuracy.[2]

5C Orbital motion

Theory review questions

1 C **2** B **3** A and C **4** B

5 C **6** D **7** C

Exam-style questions

This lesson

8 The orbital period of the satellite must be the same duration of one rotation of Saturn:

$T = (10 \text{ hr} \times 60 \text{ min/hr} \times 60 \text{ s/min}) + (41 \text{ min} \times 60 \text{ s/min}) + 57 \text{ s} = 3.9 \times 10^4 \text{ s}$

9 $4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times (2.376 \times 10^6)^2$ (1 MARK)

$r = 3.849 \times 10^8 \text{ m}$ (1 MARK)

Let R_E be the radius of the Earth, and let d be the distance from the surface of the Earth to the Moon.

$r = R_E + d \;\therefore 3.849 \times 10^8 = 6.37 \times 10^6 + d$

$d = 3.79 \times 10^8 \text{ m}$ (1 MARK)

10 [Georgina is correct, and both Alistair and Zev are incorrect.[1]] [A satellite's orbital radius is independent of its mass.[2]] [The radius of a satellite's orbit is determined by only the mass of the object being orbited, and the period (or speed) of the satellite in orbit which is shown by the relationship $r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$ $\left(\text{or } r = \frac{GM}{v^2}\right)$.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: radius of orbit being independent of masss.[2]
- I have have supported my answer with a relevant equation or explained the theory in an equivalent way.[3]

11 a $T = 365 \text{ days} \times 24 \text{ hr/day} \times 60 \text{ min/hr} \times 60 \text{ s/min}$
$= 3.154 \times 10^7 \text{ s}$ (1 MARK)

$4\pi^2 r^3 = GMT^2$ (1 MARK)

$4 \times \pi \times r^3 = 6.67 \times 10^{-11} \times 1.99 \times 10^{30} \times (3.154 \times 10^7)^2$ (1 MARK)

$r = 1.50 \times 10^{11} \text{ m}$ (1 MARK)

b $v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 1.99 \times 10^{30}}{1.495 \times 10^{11}}}$ (1 MARK)

$v = 2.98 \times 10^4 \text{ m s}^{-1}$ (1 MARK)

OR

$v = \frac{2\pi r}{T} = \frac{2 \times \pi \times 1.495 \times 10^{11}}{3.154 \times 10^7}$ (1 MARK)

$v = 2.98 \times 10^4 \text{ m s}^{-1}$ (1 MARK)

12 $4\pi^2 r^3 = GMT^2$ (1 MARK)

$4 \times \pi^2 \times (3.55 \times 10^8)^3 = 6.67 \times 10^{-11} \times M \times (5.08 \times 10^5)^2$ (1 MARK)

$M = 1.03 \times 10^{26} \text{ kg}$ (1 MARK)

13 [The satellite's speed will increase.[1]] [$v = \sqrt{\frac{GM}{r}}$, therefore $v \propto \frac{1}{\sqrt{r}}$.[2]] [Therefore if the radius of the orbit decreases, the speed of the spacecraft must increase to satisfy the equation.[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: the relationship between speed and radius.[2]
- I have related my answer to the context of the question.[3]

14 $4\pi^2 r^3 = GMT^2$ or $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$ (1 MARK)

$r = 1.74 \times 10^6 + 121 \times 10^3 = 1.86 \times 10^6 \text{ m}$ (1 MARK)

$4 \times \pi \times (1.86 \times 10^6)^3 = 6.67 \times 10^{-11} \times 7.36 \times 10^{22} \times T^2$ (1 MARK)

$T = 7.20 \times 10^3 \text{ s}$ (1 MARK)

Previous lessons

15 $KE_i = \frac{1}{2} m_{ball} u_{ball}^2 + \frac{1}{2} m_{bat} u_{bat}^2 = \frac{1}{2} \times 0.145 \times 36^2 + \frac{1}{2} \times 0.96 \times 31^2$

$KE_i = 5.6 \times 10^2 \text{ J}$ (1 MARK)

$KE_f = \frac{1}{2} m_{ball} v_{ball}^2 + \frac{1}{2} m_{bat} v_{bat}^2 = \frac{1}{2} \times 0.145 \times 49^2 + \frac{1}{2} \times 0.96 \times 18^2$

$KE_f = 3.3 \times 10^2 \text{ J}$ (1 MARK)

$KE_i > KE_f$ $\therefore$ the collision was inelastic. (1 MARK)

16 Use the inverse square law.

$F_2 = \frac{F_1}{n^2} = \frac{500}{2^2}$ (1 MARK)

$F_2 = 125 \text{ N}$ (1 MARK)

Key science skills

17 a $Gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{300 \times 10^{13} - 0}{10 \times 10^{33} - 0}$ (1 MARK)

$Gradient = 3.0 \times 10^{-19} \text{ s}^2 \text{ m}^{-3}$ (1 MARK)

b $Gradient = \frac{T^2}{r^3} = 3.0 \times 10^{-19}$

$4\pi^2 r^3 = GMT^2 \;\therefore \frac{T^2}{r^3} = \frac{4\pi^2}{GM}$ (1 MARK)

$3.0 \times 10^{-19} = \frac{4 \times \pi^2}{6.67 \times 10^{-11} \times M}$ (1 MARK)

$M = 2.0 \times 10^{30} \text{ kg}$ (1 MARK)

Chapter 5 Review

Section A

1 B **2** C **3** A **4** C **5** D

Section B

6 $v = \frac{57\,936}{3.6} = 1.61 \times 10^4 \text{ m s}^{-1}$ (1 MARK)

$v = \sqrt{\frac{GM}{r}} \;\therefore 1.61 \times 10^4 = \sqrt{\frac{6.67 \times 10^{-11} \times 1.30 \times 10^{22}}{r}}$ (1 MARK)

$r = 3.35 \times 10^3 \text{ m}$

3.35×10^3 m is less than the radius of Pluto. Therefore, New Horizons cannot orbit Pluto. (1 MARK)

7 a Area under the graph is estimated as 45 boxes (between 43 and 47 is acceptable).

Each box = $(1.0 \times 10^5 \text{ m}) \times (1.0 \text{ N kg}^{-1}) = 1.0 \times 10^5 \text{ J kg}^{-1}$ (1 MARK)

$\Delta GPE = 45 \times 1.0 \times 10^5 \times 4.49 \times 10^5$ (1 MARK)

$\Delta GPE = 2.0 \times 10^{12}$ J (1 MARK)

b $v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{5.00 \times 10^5 + 6.37 \times 10^6}}$ (1 MARK)

$v = 7620 \text{ m s}^{-1}$ (1 MARK)

$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 4.49 \times 10^5 \times 7620^2$ (1 MARK)

$KE = 1.30 \times 10^{13}$ J (1 MARK)

8 a From graph $F_g = 0.6 \times 10^2$ N (1 MARK)

Values between 0.5×10^2 N and 0.75×10^2 N acceptable.

$F_g = mg \;\therefore\; 0.6 \times 10^2 = 450 \times g$

$g = 0.13 \text{ m s}^{-2}$ or N kg^{-1} (1 MARK)

b Area under the graph is estimated as 7 boxes (between 6 and 8 is acceptable).

Each box = $(2.0 \times 10^6 \text{ m}) \times (0.5 \times 10^2 \text{ N}) = 1.0 \times 10^8$ J (1 MARK)

$\Delta KE = 7 \times 1.0 \times 10^8 = 7 \times 10^8$ J (1 MARK)

c $g = G\frac{M}{r^2} = 6.67 \times 10^{-11}\frac{1.35 \times 10^{23}}{(2.57 \times 10^6)^2}$ (1 MARK)

$g = 1.36 \text{ N kg}^{-1}$ or m s^{-2} (1 MARK)

9 a $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(6.37 \times 10^6 + 400 \times 10^3)^2}$ (1 MARK)

$g = 8.70 \text{ N kg}^{-1}$ (1 MARK)

b [No, the force of gravity is not zero.[1]][Astronauts on the ISS experience zero normal force (the force of gravity is the only force acting on them)[2]][which feels like gravity is not acting on them.[3]]

- I have explicitly addressed whether the force of gravity is zero.[1]
- I have used the relevant theory: forces in orbit.[2]
- I have explicitly addressed why astronauts do not feel gravity acting on them.[3]

10 Use inverse square law to find gravitational field strength at distance $10R_X$.

$g_2 = \frac{g_1}{\left(\frac{r_2}{r_1}\right)^2} = \frac{50}{10^2}$ (1 MARK)

$g_2 = 0.50 \text{ N kg}^{-1}$ (1 MARK)

$F_g = mg = 4.0 \times 10^3 \times 0.50 = 2.0 \times 10^3$ N (1 MARK)

11 a $T = 24$ hours

$T = 24 \times 60 \times 60 = 8.64 \times 10^4$ s

b $4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times (8.64 \times 10^4)^2$ (1 MARK)

$r = 4.225 \times 10^7$ m (1 MARK)

Distance above surface
$= r - R_E = 4.225 \times 10^7 - 6.37 \times 10^6 = 3.59 \times 10^7$ m (1 MARK)

12 a $4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 4.87 \times 10^{24} \times (8.64 \times 10^4)^2$ (1 MARK)

$r = 3.946 \times 10^7$ m (1 MARK)

$F = G\frac{M_1 M_2}{r^2} = 6.67 \times 10^{-11} \times \frac{4.87 \times 10^{24} \times 517}{(3.946 \times 10^7)^2}$ (1 MARK)

$F = 108$ N (1 MARK)

b $r = 3.946 \times 10^7$ m as calculated in part **a**.

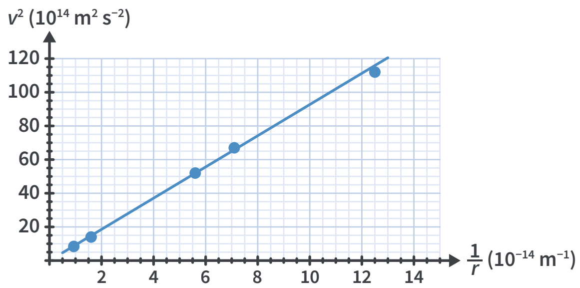
$v = \frac{2\pi r}{T} = \frac{2 \times \pi \times 3.946 \times 10^7}{8.64 \times 10^4}$ (1 MARK)

$v = 2.87 \times 10^3 \text{ m s}^{-1}$ (1 MARK)

13 a $v = \frac{2\pi r}{T} \;\therefore\; 3.8 \times 10^7 = \frac{2 \times \pi \times 6.4 \times 10^{13}}{T}$ (1 MARK)

$T = 1.1 \times 10^7$ s (1 MARK)

b



- 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 axes.
- I have plotted each point of data.
- I have drawn a straight line of best fit.

c Gradient = $\frac{rise}{run} = \frac{(93 - 5) \times 10^{14}}{(10 - 0.5) \times 10^{-14}}$ (1 MARK)

Any substitution using two points from the line of best fit is acceptable.

Gradient = $9.3 \times 10^{28} \text{ m}^3 \text{ s}^{-2}$ (1 MARK)

d $v^2 = GM \times \frac{1}{r} \;\therefore$ Gradient = GM (1 MARK)

$9.3 \times 10^{28} = 6.67 \times 10^{-11} \times M$ (1 MARK)

$M = 1.4 \times 10^{39}$ kg (1 MARK)

BONUS – CARTOON QUESTION ANSWERS

Multiple choice questions

1 D

2 A. $KE = \frac{1}{2}mv^2 \therefore 0.49 = \frac{1}{2} \times 0.500 \times v^2$

$v = 1.4\ \text{m s}^{-1}$

From the cartoon, we can see that the left sphere was stationary after the collision. So

$I = \Delta p = m\Delta v = F_{avg}\,\Delta t \therefore 0.500 \times 1.4 = F_{avg} \times 5.0 \times 10^{-3}$

$F_{avg} = 1.4 \times 10^2\ \text{N}$

Short answer questions

3 **a** $KE_i = \frac{1}{2}mv_i^2 = \frac{1}{2} \times 0.500 \times 1.4^2 = 0.49\ \text{J}$

Momentum is conserved so

$p_i = p_f \therefore m_L u_L = m_R v_R \therefore 0.500 \times 1.4 = 0.500 \times v_R$

$v_R = 1.4\ \text{m s}^{-1}$ (1 MARK)

$KE_f = \frac{1}{2}mv_f^2 = \frac{1}{2} \times 0.500 \times 1.4^2 = 0.49\ \text{J}$ (1 MARK)

$KE_i = KE_f$, therefore the collision was elastic. (1 MARK)

OR

[The collision was elastic.[1]][As only the right sphere was moving after the collision, the left sphere's momentum must have been transferred to the right sphere in order for momentum to be conserved, so $p = m_L u_L = m_R v_R$. Since $m_L = m_R$, this equation tells us $u_L = v_R$ as well.[2]][Hence $KE_i = \frac{1}{2}m_L u_L^2 = \frac{1}{2}m_R u_R^2 = KE_f$, so the collision was elastic.[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: conservation of momentum.[2]
- I have used the relevant theory: elastic collisions.[3]

b Yes, the right sphere achieved the same maximum height.

As kinetic energy is conserved in an elastic collision, the maximum GPE of the right sphere, and hence its maximum height, was the same as the left sphere's.

4 $F = G\frac{M_1M_2}{r^2} = 6.67 \times 10^{-11} \times \frac{0.500 \times 0.500}{0.15^2}$ (1 MARK)

$F = 7.4 \times 10^{-10}\ \text{N}$ (1 MARK)

6A Electric fields

Theory review questions

1 H **2** B **3** D **4** G

5 A **6** C

Exam-style questions

This lesson

7 C

8

9 C

10 **a** $E = \frac{V}{d}$ $\therefore 6.0 \times 10^5 = \frac{V}{0.15}$

$V = 90 \times 10^3$ V = 90 kV

b $\frac{1}{2}mv^2 = qV$ $\therefore \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = 1.6 \times 10^{-19} \times 90 \times 10^3$ (1 MARK)

$v = 1.8 \times 10^8$ m s^{-1} (1 MARK)

11 **a** $E = \frac{V}{d} = \frac{1.67 \times 10^3}{0.30}$ (1 MARK)

$E = 5.57 \times 10^3 = 5.6 \times 10^3$ V m^{-1} or N C^{-1} (1 MARK)

b $F = qE$ and $F = mg$ $\therefore mg = qE$

$m \times 9.8 = 4.00 \times 10^{-5} \times 5.57 \times 10^3$ (1 MARK)

$m = 2.3 \times 10^{-2}$ kg (1 MARK)

12 $\frac{1}{2}mv^2 = qV$ and $E = \frac{V}{d}$

$\frac{1}{2}mv^2 = qEd$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times (6.3 \times 10^6)^2 = 1.6 \times 10^{-19} \times 2.0 \times 10^3 \times d$ (1 MARK)

$d = 5.6 \times 10^{-2}$ m = 5.6 cm (1 MARK)

13 **a** To the right (the electric field due to a positive charge points away from the charge).

b $F = \frac{kq_1q_2}{r^2} = \frac{8.99 \times 10^9 \times 3.4 \times 10^{-8} \times 5.4 \times 10^{-9}}{(3.0 \times 10^{-3})^2} = 0.18$ N to the left (2 MARKS)

c From the inverse square law, $F_2 = \frac{F_1}{n^2}$ where $n = \frac{r_2}{r_1} = 3$

$F = \frac{0.18}{3^2} = 0.020$ N to the left (2 MARKS)

Previous lessons

14 **a** $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 2.5 \times 22^2 = 6.1 \times 10^2$ J

b $KE_i + GPE_i = KE_{top} + GPE_{top}$

$KE_i = GPE_{top}$ $\therefore 6.1 \times 10^2 = 2.5 \times 9.8 \times h$ (1 MARK)

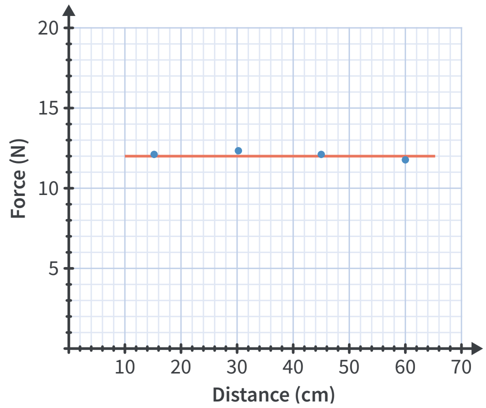
$h = 25$ m (1 MARK)

15 $F = G\frac{M_1M_2}{r^2}$ $\therefore 230 = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24} \times M}{(9.00 \times 10^6)^2}$ (1 MARK)

$M = 46.7$ kg (1 MARK)

Key science skills

16 **a**



- I have labelled the independent variable (distance) on the horizontal axis with units.
- I have labelled the dependent variable (force) on the vertical axis with units.
- I have used an appropriate and consistent scale.
- I have plotted each point of data.
- I have drawn a line of best fit.

b [The field is uniform in this region[1]][as the force on the charged object remains constant irrespective of its location within the field.[2]]

- I have explicitly addressed whether the field is uniform or non-uniform.[1]
- I have used the relevant theory: force on a charged particle within a uniform electric field.[2]

6B Magnetic fields

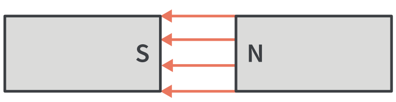
Theory review questions

1 B **2** C **3** B **4** A **5** C

Exam-style questions

This lesson

6 **a** **i**

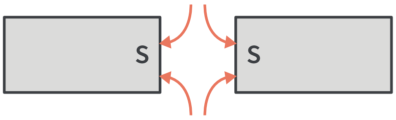


- I have drawn 4 field lines.
- I have drawn magnetic field lines that do not touch or cross.
- I have included arrowheads to show direction.
- I have drawn a uniform magnetic field from the north to the south pole.

ii Uniform field

6B

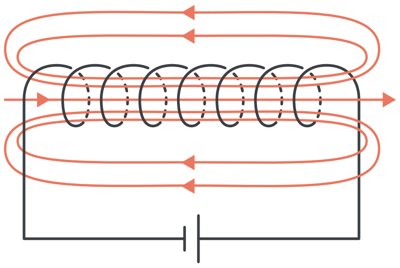
b i



- I have drawn 4 field lines.
- I have drawn magnetic field lines that do not touch or cross.
- I have included arrowheads to show direction.
- I have drawn a non-uniform magnetic field towards the south poles.

ii Non-uniform field

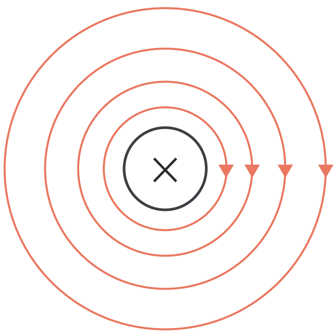
c i



- I have drawn 5 field lines.
- I have drawn magnetic field lines that do not touch or cross.
- I have included arrowheads to show direction.
- I have drawn a magnetic field in the direction determined by the right-hand coil rule.

ii Uniform field inside the solenoid

d i



- I have drawn 4 field lines.
- I have drawn magnetic field lines that do not touch or cross.
- I have included arrowheads to show direction.
- I have drawn a circular magnetic field lines around the wire, with direction determined by the right-hand grip rule.

ii Non-uniform field

7 A. Field direction is determined using the right-hand grip rule.

8 D

9 Since *W* and *X* are repelling each other, they must be the same pole. Since the field lines are going into the poles, they are south poles. *W* is a south pole, *X* is a south pole. (1 MARK)

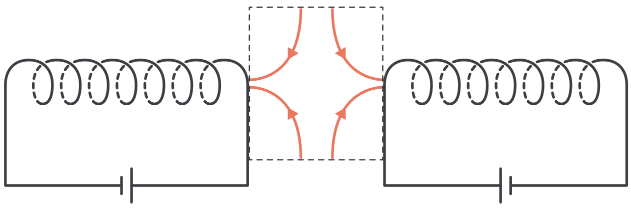
Since the field lines are uniform and flowing from *Y* to *Z*: *Y* is a north pole, *Z* is a south pole. (1 MARK)

10 The north point of the compass would point in direction A. Using the right-hand coil rule, the magnetic field of the solenoid would be pointing to the left where the compass is.

11 [E could be a magnetic field.[1]][F cannot be a magnetic field[2]][since it represents a monopole, and there is no known magnetic monopole.[3]]

- I have explicitly addressed if E could be a magnetic field.[1]
- I have explicitly addressed if F could be a magnetic field.[2]
- I have used the relevant theory: magnetic monopoles.[3]

12



- I have drawn four field lines with arrows to show direction.
- I have used the right-hand coil rule to find the direction of the magnetic field of each solenoid.
- I have drawn magnetic field lines that do not touch or cross.

13 The current is travelling upwards. Note that this is determined using the right-hand grip rule.

Previous lessons

14 $v = \sqrt{-2g\Delta h + u^2} = \sqrt{-2 \times 9.8 \times (0 - 1000) + 0^2}$ (1 MARK)

$v = 1.4 \times 10^2$ m s^{-1} (1 MARK)

15 Approximately 11 squares under the graph (between 10 and 12 acceptable) (1 MARK)

Area of each square $= (2 \times 10^8 \text{ m}) \times (20 \text{ N kg}^{-1}) = 40 \times 10^8 \text{ J kg}^{-1}$

$\Delta GPE = 11 \times 40 \times 10^8 \times 200$ (1 MARK)

$\Delta GPE = 8.8 \times 10^{12}$ J (1 MARK)

Key science skills

16 Uncertainty $= \frac{1}{2} \times$ smallest gradation on scale $= \frac{1}{2} \times 10° = 5°$

6C Magnetic forces on charged particles

Theory review questions

1 Yes **2** No **3** No **4** C

5 A **6** B and C **7** C

Exam-style questions

This lesson

8 a $F = qvB = 1.6 \times 10^{-19} \times 2000 \times 0.030$ (1 MARK)

$F = 9.6 \times 10^{-18}$ N (1 MARK)

b Using the right-hand palm rule: the direction of the force is downwards.

c Using the right-hand palm rule with direction of motion reversed: the direction of the force is upwards.

9 a $F = qvB \;\therefore 2.00 \times 10^{-11} = 1.6 \times 10^{-19} \times v \times 3.00$

$v = 4.2 \times 10^{7}$ m s^{-1}

b $r = \dfrac{mv}{qB} = \dfrac{9.1 \times 10^{-31} \times 4.2 \times 10^{7}}{1.6 \times 10^{-19} \times 3.00}$ (1 MARK)

$r = 8.0 \times 10^{-5}$ m (1 MARK)

10 [The magnetic force on a charged particle moving perpendicular to a magnetic field is always perpendicular to the direction of motion and is constant in magnitude.[1]][In the absence of other forces, the magnetic force acts as the centripetal force and causes uniform circular motion, which is sustained since the magnetic field will remain perpendicular to the motion of the particle.[2]]

I have used the relevant theory: circular motion in magnetic fields.[1]

I have explicitly addressed why a charged particle exhibits uniform circular motion.[2]

I have used the relevant theory: uniform circular motion.

11 a $F = nILB = 1 \times 1.50 \times 0.100 \times 0.400 = 6.00 \times 10^{-2}$ N

b Using the right-hand palm rule: the force acts into the page.

12 a Sides XY and WZ experience a force.
Note that this is because these sides carry current perpendicular to the magnetic field, whereas the other two sides carry current parallel to the field.

b $F = nILB = 10 \times 2.50 \times 2.00 \times 6.50 \times 10^{-6}$ (1 MARK)

$F = 3.25 \times 10^{-4}$ N for each side (1 MARK)

c Using the right-hand palm rule:
the side XY experiences an upward force. (1 MARK)
the side WZ experiences a downward force. (1 MARK)

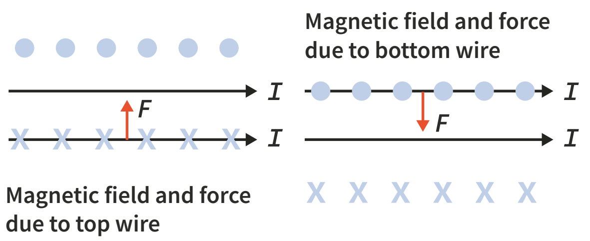
13 B. Use right-hand palm rule with fingers pointing out of the page and palm pointing towards the centre of the circle. This shows clockwise motion for a positive charge, which means anticlockwise motion for an electron.

14 a $r = \dfrac{mv}{qB} \;\therefore 1.0 = \dfrac{9.1 \times 10^{-31} \times 2.5 \times 10^{5}}{1.6 \times 10^{-19} \times B}$ (1 MARK)

$B = 1.4 \times 10^{-6}$ T (1 MARK)

b $a = \dfrac{v^2}{r} = \dfrac{(2.5 \times 10^{5})^2}{1.0} = 6.3 \times 10^{10}$ m s^{-2}

15 a The wires are attracted to each other when they carry current in the same direction.
Take the current to flow to the right in both wires. By the right-hand grip rule, the field due to the upper wire is into the page at the location of the lower wire. The right-hand palm rule predicts an upwards force on the lower wire.
By the right-hand grip rule, the field due to the lower wire is out of the page at the location of the upper wire. The right-hand palm rule predicts a downwards force on the upper wire.

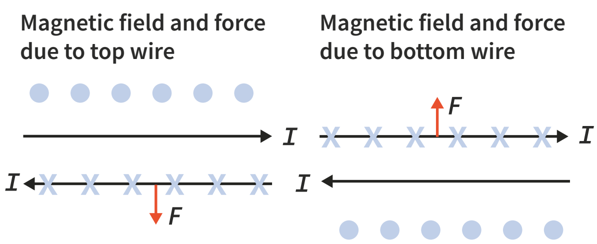


I have stated whether the wires are attracted or repelled from each other.

I have included a sketch to justify my answer.

I have drawn the magnetic field created by each wire and the associated forces.

b The wires are repelled from each other when they carry current in the opposite direction.
Take the current to flow to the right in the upper wire and to the left in the lower wire. By the right-hand grip rule, the field due to the upper wire is into the page at the location of the lower wire. The right-hand palm rule predicts a downwards force on the lower wire.
By the right-hand grip rule, the field due to the lower wire is into the page at the location of the upper wire. The right-hand palm rule predicts an upwards force on the upper wire.



I have stated whether the wires are attracted or repelled from each other.

I have included a sketch to justify my answer.

I have drawn the magnetic field created by each wire and the associated forces.

Previous lessons

16 $Gradient = \frac{rise}{run} = \frac{F}{\Delta x} = k$ (1 MARK)

$k = \frac{100 - 0}{0.2 - 0} = 500 \text{ N m}^{-1}$ (1 MARK)

17 $r = 2000 \times 10^3 + 6.37 \times 10^6 = 8.37 \times 10^6$ m (1 MARK)

$a = \frac{v^2}{r} = \frac{6900^2}{8.37 \times 10^6} = 5.69 \text{ m s}^{-2}$ (1 MARK)

OR

$r = 2000 \times 10^3 + 6.37 \times 10^6 = 8.37 \times 10^6$ m (1 MARK)

$a = g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(8.37 \times 10^6)^2} = 5.69 \text{ m s}^{-2}$ (1 MARK)

Key science skills

18 Independent: magnitude of particles' charge. (1 MARK)

Dependent: radius of circular motion within magnetic field. (1 MARK)

Controlled: magnetic field strength **OR** particle mass **OR** particle speed. (1 MARK)

6D DC motors

Theory review questions

1 A	**2** A	**3** D	**4** B
5 C	**6** A		

Exam-style questions

This lesson

7 a D. The force is zero if the current is parallel to the magnetic field.

b [The best position to start the motor from rest is the horizontal position.[1]][In this position, the force exerted on the sides of the coil acts to create the maximum turning effect (or torque).[2]]

- I have explicitly addressed the best position to start the motor.[1]
- I have used the relevant theory: turning effect or torque.[2]

c B (1 MARK)

Increasing the voltage of the battery will act to increase the current in the coil, which increases the force ($F = nILB$) and therefore the speed of rotation. (1 MARK)

8 a $F = nILB = 80 \times 2.5 \times 0.10 \times 2.0 \times 10^{-3}$ (1 MARK)

$F = 4.0 \times 10^{-2}$ N in the direction D. (2 MARKS)

b [The force on side *TU* is zero[1]][as the current through *TU* runs parallel to the magnetic field.[2]]

- I have explicitly addressed the force on side *TU*.[1]
- I have used the relevant theory: conditions for force on a current-carrying wire.[2]

c [A split ring commutator in a DC motor reverses the direction of current in the coil every half rotation so that the force on each side reverses direction every half turn.[1]][Therefore the split ring commutator keeps the coil rotating in a constant direction.[2]]

- I have used the relevant theory: operation of a split ring commutator.[1]
- I have explicitly addressed the role of the split ring commutator.[2]

9 a [The motor will rotate anticlockwise (A).[1]][The current flows from *M* to *N* (and *O* to *P*)[2]][and the magnetic field points to the right.[3]][By the right-hand palm rule, the force on side *MN* is downwards (and the force on side *OP* is upwards).[4]]

- I have explicitly addressed the direction of rotation.[1]
- I have identified the direction of current around the loop.[2]
- I have identified the direction of the magnetic field.[3]
- I have used the relevant theory: right-hand palm rule to determine direction of force.[4]

b [The motor would no longer function.[1]][The coil would rotate one-quarter of a revolution where it will oscillate around the vertical position and eventually stop.[2]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: slip rings in DC motors.[2]

Previous lessons

10 a When the mass is stationary, it is in equilibrium. Any data set with non-zero mass can be used. Our answer uses 3 masses.

$mg = k\Delta x \;\therefore 3 \times 30 \times 10^{-3} \times 9.8 = k \times 0.15$ (1 MARK)

$k = 5.88 = 5.9 \text{ N m}^{-1}$ (1 MARK)

b Take the gravitational potential energy to be zero at the lowest point of oscillation.

$GPE_{top} = SPE_{bot} \;\therefore mgh = \frac{1}{2}k(\Delta x)^2$

$5 \times 0.030 \times 9.8 \times h = \frac{1}{2} \times 5.88 \times (\Delta x)^2$ (1 MARK)

$h = \Delta x$ since the top of the oscillation is the unstretched position.

$\Delta x = 0.50$ m (1 MARK)

$L = 0.60 + 0.50 = 1.10$ m (1 MARK)

11 $T = 7.40 \times 10^5 \times 60 \times 60 = 2.664 \times 10^9$ s (1 MARK)

$4\pi^2 r^3 = GMT^2$ (1 MARK)

$4 \times \pi^2 \times (2.87 \times 10^{12})^3 = 6.67 \times 10^{-11} \times M \times (2.664 \times 10^9)^2$ (1 MARK)

$M = 1.97 \times 10^{30}$ kg (1 MARK)

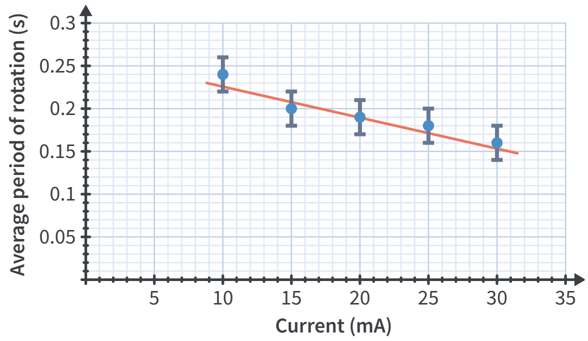
Key science skills

12 a Independent: current. (1 MARK)

Dependent: Period of rotation. (1 MARK)

Controlled: Number of loops **OR** length of wire **OR** magnetic field strength (1 MARK)

b



- I have drawn current on the horizontal axis.
- I have drawn average period of rotation 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 included a line of best fit that passes through all the uncertainty bars.

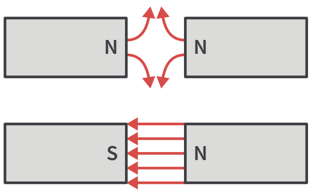
Chapter 6 Review

Section A

1 B **2** A **3** D **4** C **5** D

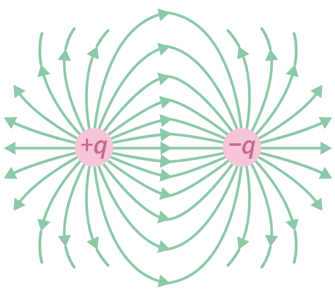
Section B

6



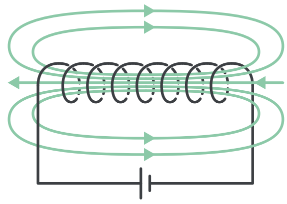
- I have drawn at least 4 field lines for each pair of magnets.
- I have drawn the correct magnetic field pattern.
- I have included arrowheads to show direction.

7



- I have drawn at least 5 field lines.
- I have drawn the correct electric field pattern.
- I have included arrowheads to show direction.

8



- I have drawn 5 magnetic field lines.
- I have drawn the correct magnetic field pattern.
- I have included arrowheads to show direction.

9 $F = nILB = 1 \times 6.6 \times 3.2 \times 3.1 \times 10^{-5}$ (1 MARK)

$F = 6.5 \times 10^{-4}$ N (1 MARK)

Direction of force is to the east by the right-hand palm rule. (1 MARK)

10 a [The north pole of the compass would point up the page.[1]] [The compass would align with the magnetic field (which points upwards)[2]][produced by the two solenoids whose inner ends both act as south poles by the right-hand grip rule.[3]]

- I have explicitly stated the direction of the compass.[1]
- I have used the relevant theory: magnetic fields.[2]
- I have used the relevant theory: right-hand grip rule.[3]

b [The force on the wire will be zero[1]][because the magnetic field is parallel to the current flowing in the wire.[2]]

- I have explicitly addressed the direction of the force on the wire.[1]
- I have used the relevant theory: force on a current-carrying wire.[2]

11 a $F = nILB \therefore 4.0 = 100 \times 1.75 \times L \times 750 \times 10^{-3}$ (1 MARK)

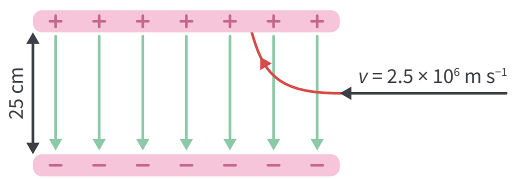
$L = 3.0 \times 10^{-2}$ m (1 MARK)

b [The motor would vibrate and eventually stop[1]][in a position such that the coil is perpendicular to the magnetic field because the direction of the forces on the coil would be constantly rotating it to this position.[2]][This is because slip rings would cause the current to flow around the coil in a constant direction rather than changing direction every half turn.[3]]

- I have explicitly addressed how the operation of the motor is affected.[1]
- I have used the relevant theory: DC motors.[2]
- I have used the relevant theory: slip rings.[3]

12 a $E = \frac{V}{d} \therefore 7.0 \times 10^3 = \frac{V}{25 \times 10^{-2}}$ (1 MARK)

$V = 1.8 \times 10^3$ V (1 MARK)

b 

I have drawn the path of the electron moving towards the positive plate.

I have drawn a parabolic path.

c $d = \frac{1}{2} \times 25 \times 10^{-2} = 0.125$ m

$\Delta KE = W = qEd = 1.6 \times 10^{-19} \times 7.0 \times 10^{3} \times 0.125$ (1 MARK)

$\Delta KE = 1.4 \times 10^{-16}$ J (1 MARK)

13 **a** $E = \frac{kq}{r^2} = \frac{8.99 \times 10^9 \times 4.0 \times 10^{-7}}{2.25^2}$ (1 MARK)

$E = 7.1 \times 10^2$ N C^{-1} or V m^{-1} (1 MARK)

b $F = \frac{kq_1q_2}{r^2} = \frac{8.99 \times 10^9 \times 4.0 \times 10^{-7} \times 1.6 \times 10^{-19}}{2.25^2}$ (1 MARK)

$F = 1.1 \times 10^{-16}$ N (1 MARK)

14 **a** [The force on side *BC* is zero.[1]][In the orientation shown, the current flowing in side *BC* is parallel to the magnetic field and hence will experience no magnetic force.[2]]

I have explicitly stated the force on side *BC*.[1]

I have used the relevant theory: force on a current-carrying wire.[2]

b $F = nILB = 1 \times 3.5 \times 15.0 \times 10^{-2} \times 45.0 \times 10^{-3}$ (1 MARK)

$F = 2.4 \times 10^{-2}$ N (1 MARK)

By the right-hand palm rule, the force on side *CD* is downwards. (1 MARK)

c [The function of a split ring commutator is to reverse the direction of the current in the loop every half rotation.[1]] [This results in the turning effect on the loop acting in a constant direction and causes continuous rotation of the motor.[2]]

I have explicitly stated the function of a split ring commutator.[1]

I have used the relevant theory: split ring commutator.[2]

d [The best orientation to start the DC motor is in the horizontal position.[1]][In this orientation the force on sides *AB* and *CD* creates the maximum turning effect (torque).[2]]

I have explicitly stated the best orientation.[1]

I have used the relevant theory: DC motor operation.[2]

15 **a** $\frac{1}{2}mv^2 = W = qV \therefore V = \frac{\frac{1}{2}mv^2}{q}$ (1 MARK)

$V = \frac{\frac{1}{2} \times 1.7 \times 10^{-27} \times (1.84 \times 10^6)^2}{1.6 \times 10^{-19}}$ (1 MARK)

$V = 1.8 \times 10^4$ V (1 MARK)

b $F = qE = q \times \frac{V}{d} = 1.6 \times 10^{-19} \times \frac{1.8 \times 10^4}{0.75}$ (1 MARK)

$F = 3.8 \times 10^{-15}$ N (1 MARK)

c $F = qvB = 1.6 \times 10^{-19} \times 1.84 \times 10^6 \times 35.0 \times 10^{-3}$ (1 MARK)

$F = 1.0 \times 10^{-14}$ N (1 MARK)

d $r = \frac{mv}{qB} = \frac{1.7 \times 10^{-27} \times 1.84 \times 10^6}{1.6 \times 10^{-19} \times 35.0 \times 10^{-3}}$ (1 MARK)

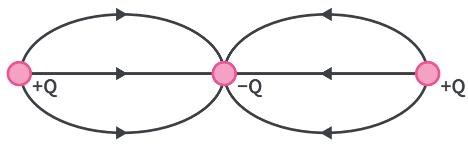
$r = 0.56$ m (1 MARK)

Unit 3, AOS 1 Review

Section A

1 C **2** A **3** B **4** C **5** B

Section B

6 **a** 

I have drawn 6 field lines which do not touch or cross.

I have included arrowheads to show direction.

I have drawn an electric field from positive to negative charge.

b The field is non-uniform.

7 **a** $E = \frac{kq}{r^2} = \frac{9.0 \times 10^9 \times 2.4 \times 10^{-6}}{(5.3 \times 10^{-2})^2}$ (1 MARK)

$E = 7.7 \times 10^6$ N C^{-1} (1 MARK)

b $F = \frac{mv^2}{r}$ (1 MARK)

$18.5 = \frac{25 \times 10^{-3} \times v^2}{5.3 \times 10^{-2}}$ (1 MARK)

$v = 6.3$ m s^{-1} (1 MARK)

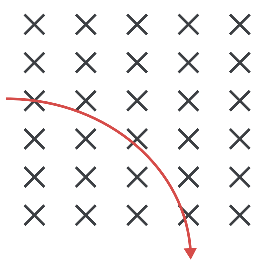
8 **a** $\frac{1}{2}mv^2 = qV$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = 1.6 \times 10^{-19} \times 14 \times 10^{-3}$ (1 MARK)

$v = 7.0 \times 10^4$ m s^{-1} (1 MARK)

b $E = \frac{V}{d} \therefore 2.0 \times 10^{-2} = \frac{14 \times 10^{-3}}{d}$ (1 MARK)

$d = 0.70$ m (1 MARK)

c 

I have drawn a circular path.

I have drawn a clockwise path.

9 a [The path is circular since the magnetic force has a constant magnitude[1]][and its direction is always at right angles to the proton's velocity (the same characteristics as a centripetal force).[2]][This is because the velocity of the proton is at right angles to the magnetic field.[3]]

- I have used the relevant theory: magnitude of centripetal force for uniform circular motion.[1]
- I have used the relevant theory: direction of centripetal force.[2]
- I have used the relevant theory: force on a charged particle in a magnetic field.[3]
- I have explicitly addressed the reason the path is circular.

b $r = \frac{mv}{qB} = \frac{1.67 \times 10^{-27} \times 5.00 \times 10^{7}}{1.60 \times 10^{-19} \times 500 \times 10^{-3}}$ (1 MARK)

$r = 1.04$ m (1 MARK)

c $F = qvB = 1.60 \times 10^{-19} \times 5.00 \times 10^{7} \times 500 \times 10^{-3}$ (1 MARK)

$F = 4.00 \times 10^{-12}$ N (1 MARK)

10 a $r = 3.4 \times 10^{6} + 8.39 \times 10^{5} = 4.24 \times 10^{6}$ m (1 MARK)

$4\pi^2 r^3 = GMT^2$ (1 MARK)

$4 \times \pi^2 \times (4.24 \times 10^{6})^3 = 6.67 \times 10^{-11} \times 6.4 \times 10^{23} \times T^2$ (1 MARK)

$T = 8.4 \times 10^{3}$ s (1 MARK)

b [When radius decreases, speed will need to increase.[1]][This is shown through the relationship $v = \sqrt{\frac{GM}{r}}$, where speed is inversely proportional to the square root of the radius.[2]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: speed is inversely proportional to the square root of the radius.[2]

c [The total energy of a satellite is a combination of kinetic and gravitational potential energy.[1]][Since the speed of the satellite will increase, as shown in part **b**, the kinetic energy must increase.[2]][Therefore, the gravitational potential energy will decrease.[3]]

- I have used the relevant theory: conservation of energy.[1]
- I have used the relevant theory: relationship between speed and kinetic energy.[2]
- I have explicitly addressed the question.[3]

11 a Out of the page

b $F = nILB = 1 \times 958 \times 1 \times 8.0 \times 10^{-5}$ (1 MARK)

$F = 7.7 \times 10^{-2}$ N (1 MARK)

c [The force is 0 N[1]][as the current running through side CD is parallel to the direction of Earth's magnetic field.[2]]

- I have explicitly addressed the magnitude of the force acting on side CD.[1]
- I have used the relevant theory: force on a current-carrying wire parallel to a magnetic field.[2]

12 a [The motor will rotate anticlockwise.[1]][The current flows from H to G (and F to E)[2]][and the magnetic field points to the left.[3]][By the right-hand palm rule, the force on side HG is upwards (and the force on side FE is downwards).[4]]

- I have explicitly addressed the direction of rotation.[1]
- I have identified the direction of current around the loop.[2]
- I have identified the direction of the magnetic field.[3]
- I have used the relevant theory: right-hand palm rule to determine direction of force.[4]

b 0 N. The forces on the whole motor are balanced.

c $F = nILB = 30 \times 1.5 \times 0.20 \times 4.0 \times 10^{-3}$ (1 MARK)

$F = 3.6 \times 10^{-2}$ N (1 MARK)

d 0 N. Side FG is parallel to the magnetic field.

e [A split ring commutator reverses the direction of the current every half turn.[1]][This ensures that the force produced on each side always acts to turn the motor in a constant direction.[2]]

- I have used the relevant theory: split ring commutator in a DC motor.[1]
- I have explicitly addressed the role of a commutator.[2]

f [The motor would no longer function.[1]][The loop would rotate one-quarter of a revolution to the vertical position and oscillate there, eventually coming to a stop, since the force on each side would always act to return the motor to the vertical position.[2]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: slip rings in a DC motor.[2]

REVIEW

7A EMF and Faraday's law

Theory review questions

1 B, C, A, D

2 D

3 a B, D
b A, B, C, D

4 A

5 Q: zero, R: negative, S: positive

6 C

Exam-style questions

This lesson

7 a $\Phi_B = B_\perp A = 0 \times 0.10 \times 0.10 = 0$ Wb (the magnetic field strength is zero at that point)

b $\Phi_B = B_\perp A = 0.15 \times 0.10 \times 0.10 = 1.5 \times 10^{-3}$ Wb

c $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 20 \times \frac{1.5\times10^{-3}-0}{0.25}$ (1 MARK)

Magnitude of average EMF is 0.12 V (1 MARK)

8 a A

b B

c At $t = 0$ s: $\Phi_B = B_\perp A = 0.040 \times 0 = 0$ Wb

2.5×10^3 cm^2 = 0.25 m^2

At $t = 2$ s: $\Phi_B = B_\perp A = 0.040 \times 0.25 = 1.0 \times 10^{-2}$ Wb

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 15 \times \frac{1.0\times10^{-2}-0}{2-0}$ (1 MARK)

Magnitude of average EMF is 7.5×10^{-2} V. (1 MARK)

9 C and D. These two options would both cause a change in the area of the loop that is inside and perpendicular to the magnetic field, so that the flux would change.

10 a When the rate of change of magnetic flux is zero the emf will also be zero.

$t = 0, 1, 2, 3, 4, 5$ s

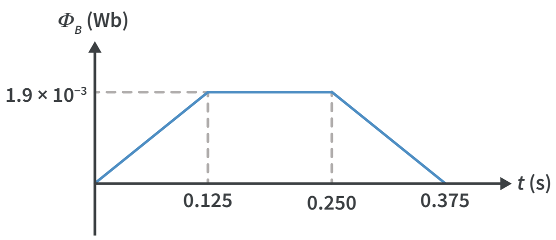
b $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 4 \times \frac{2.5-0.5}{2.0-1.0}$ (1 MARK)

$\varepsilon = 8.0$ V (1 MARK)

c When the magnetic flux is a maximum the magnet is in the middle of the loop.

$t = 1.0, 3.0, 5.0$ s

11 a Maximum flux when entirely within magnetic field:
$\Phi_B = B_\perp A = 3.0\times10^{-2}\times(0.25\times0.25) = 1.875\times10^{-3} = 1.9\times10^{-3}$ Wb
Coil must move 25 cm to be entirely within magnetic field, another 25 cm to begin leaving the field, and another 25 cm to be entirely outside the field again. Time for each stage:
$\Delta t = \frac{\Delta s}{v} = \frac{0.25}{2} = 0.125$ s



I have shown the magnitude of the magnetic flux to increase at a constant rate when the loop enters the field.

I have shown the magnetic flux to stay constant when the loop is entirely within the field.

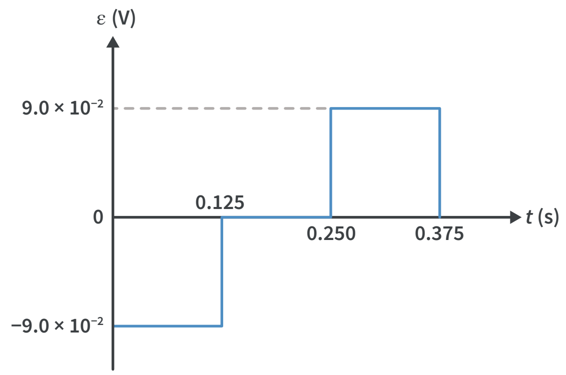
I have shown the magnitude of the magnetic flux to decrease at a constant rate when the loop exits the field.

I have included the value of the maximum magnitude of magnetic flux.

I have included the time for each stage of the motion.

Note that the inverse graph (all flux values negative) is also acceptable.

b $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 6 \times \frac{1.875\times10^{-3}}{0.125} = 9.0 \times 10^{-2}$ V



I have drawn a constant EMF when the rate of change of magnetic flux is constant.

I have drawn zero EMF when the rate of change of magnetic flux is zero.

I have used the opposite sign for the EMF when the flux is increasing compared to when the flux is decreasing.

I have included the values of the maximum magnitudes of EMF.

I have included the time for each stage of the motion.

Note that the inverse graph is also acceptable.

Previous lessons

12 a $GPE_A = KE_B + GPE_B \therefore mgh_A = \frac{1}{2}mv_B^2 + mgh_B$ (1 MARK)

$0.400 \times 9.8 \times h_A = \frac{1}{2} \times 0.400 \times 4.0^2 + 0.400 \times 9.8 \times 0.30$ (1 MARK)

$h_A = 1.1$ m (1 MARK)

b $F_{net} = F_N + F_g$ (1 MARK)

$\frac{mv^2}{r} = F_N + mg \therefore \frac{0.400\times4.0^2}{0.15} = F_N + 0.400 \times 9.8$ (1 MARK)

$F_N = 39$ N (1 MARK)

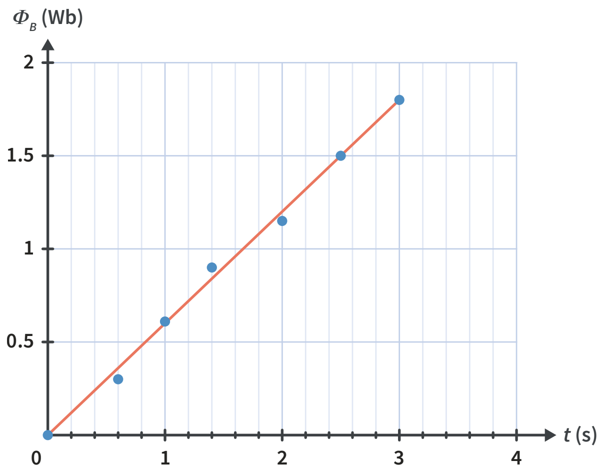
13 $F = k\frac{q_1q_2}{r^2} = 8.99 \times 10^9 \times \frac{1.6 \times 10^{-19} \times 3.50 \times 10^{-10}}{0.002^2}$ (1 MARK)

The direction is to the right as two positive charges will repel.

$F = 1.3 \times 10^{-13}$ N to the right. (2 MARKS)

Key science skills

14 a



- I have correctly labelled both axes, including units.
- I have included appropriate and consistent scales.
- I have correctly plotted each point of data.
- I have drawn a line of best fit.

b $Gradient = \frac{1.8-0}{3-0} = 0.6$ Wb s^{-1} (1 MARK)

$Gradient = \frac{\Delta\Phi_B}{\Delta t}$ and $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$ (magnitude only)

$\therefore \varepsilon = N \times gradient$ (1 MARK)

$6 = N \times 0.6$

$N = 10$ (1 MARK)

7B Direction of induced current and Lenz's law

Theory review questions

1 C	**2** B	**3** B	**4** C
5 D	**6** A		

Exam-style questions

This lesson

7 a [The magnetic flux through the coil as the magnet falls from position 1 to position 2 is increasing[1]][downwards.[2]][By Lenz's law, the induced magnetic field will oppose this change in flux,[3]][so it will be directed upwards.[4]][Using the right-hand coil rule,[5]][the induced current will flow in an anticlockwise direction when viewed from above.[6]]

- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]
- I have explicitly addressed the direction of magnetic flux.[2]
- I have used the relevant theory: Lenz's law.[3]
- I have explicitly addressed the direction of the induced magnetic field.[4]
- I have explicitly referenced the right-hand coil rule.[5]
- I have explicitly stated the direction of the induced current.[6]

b [The current is flowing clockwise.[1]][This change is due to the magnetic flux now decreasing downwards rather than increasing downwards.[2]]

- I have explicitly stated the direction of the induced current.[1]
- I have explicitly addressed the difference between the two situations responsible for the change.[2]

8 [The magnetic flux through the loop of wire as it exits the magnetic field is decreasing[1]][upwards (out of the page when viewed from above).[2]][By Lenz's law, the induced magnetic field will oppose this change in flux,[3]][so it will be directed up (out of the page).[4]][Using the right-hand coil rule,[5]][the induced current will flow from *X* to *Y* through the ammeter.[6]]

- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]
- I have explicitly addressed the direction of magnetic flux.[2]
- I have used the relevant theory: Lenz's law.[3]
- I have explicitly addressed the direction of the induced magnetic field.[4]
- I have explicitly referenced the right-hand coil rule.[5]
- I have explicitly stated the direction of the induced current.[6]

9 a [Using the right-hand coil rule, the solenoid produces a magnetic field which acts to the left along its long axis.[1]][The magnetic flux through the loop of wire as it moves away from the solenoid is decreasing[2]][to the left.[3]][By Lenz's law, the induced magnetic field will oppose this change in flux,[4]][so it will be directed to the left.[5]][Using the right-hand coil rule,[6]][the induced current will flow in an anticlockwise direction when viewed from the solenoid.[7]]

- I have explicitly referenced the right-hand coil rule to determine the solenoid's magnetic field.[1]
- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[2]
- I have explicitly addressed the direction of the magnetic flux through the loop.[3]
- I have used the relevant theory: Lenz's law.[4]

- I have explicitly addressed the direction of the induced magnetic field.[5]
- I have explicitly referenced the right-hand coil rule.[6]
- I have explicitly stated the direction of the induced current.[7]

b [The current is flowing out of the right side of the cell and into the left side of the cell[1]][so the cell must be connected in orientation *B*.[2]]

Explanation: Using the right-hand coil rule, the anticlockwise induced current as viewed from the solenoid means the induced magnetic field is to the left through the loop. By Lenz's law, this induced current must create a magnetic field to oppose the initial change in flux. The flux is increasing since the loop is approaching the solenoid. Hence the initial change in flux was increasing to the right. For this to occur when the loop approaches the solenoid, the right side of the solenoid must be acting as a north pole. Using the right-hand coil rule, current must flow left to right through the cell, which is consistent with orientation *B*.

- I have explicitly addressed the direction current is flowing through the solenoid circuit.[1]
- I have explicitly addressed the orientation of the cell.[2]

Previous lessons

10 a $SPE_{bot} = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 29.4 \times 1.00^2$ (1 MARK)

$SPE_{bot} = 14.7$ J (1 MARK)

OR

$SPE_{bot} = GPE_{top} = mgh_{top} = 1.50 \times 9.8 \times 1.00$ (1 MARK)

$SPE_{bot} = 14.7 = 15$ J (1 MARK)

b The speed will be at a maximum when its acceleration is zero, which is at the midpoint.

$KE_{bot} + GPE_{bot} + SPE_{bot} = KE_{mid} + GPE_{mid} + SPE_{mid}$

$SPE_{bot} = KE_{mid} + GPE_{mid} + SPE_{mid}$ $\therefore 14.7 = \frac{1}{2}mv^2 + mgh + \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$14.7 = \frac{1}{2} \times 1.50 \times v^2 + 1.50 \times 9.8 \times 0.50 + \frac{1}{2} \times 29.4 \times 0.50^2$ (1 MARK)

$v = 2.2$ m s^{-1} (1 MARK)

c [B is the correct graph.[1]][At the top, the acceleration is downwards because the only force is the force due to gravity.[2]][The spring force on the mass is directed upwards and it increases directly with the extension[3]][so that the net force and acceleration is zero at the midpoint[4]][and it is upwards at the lowest point.[5]]

- I have identified the correct graph.[1]
- I have explicitly addressed the acceleration at the top.[2]
- I have used the relevant theory: the relationship between spring force and extension.[3]
- I have explicitly addressed the acceleration at the midpoint.[4]
- I have explicitly addressed the acceleration at the lowest point.[5]

11 a $E = \frac{V}{d} = \frac{10\,000}{0.075}$ (1 MARK)

$E = 1.3 \times 10^5$ V m^{-1} or N C^{-1} (2 MARKS)

b $qV = \frac{1}{2}mv^2$ $\therefore 1.6 \times 10^{-19} \times 10\,000 = 0.5 \times 1.7 \times 10^{-27} \times v^2$ (1 MARK)

$v = 1.4 \times 10^6$ m s^{-1} (1 MARK)

Key science skills

12 Independent variable: Direction of magnet's motion **OR** the directional change in magnetic flux

Dependent variable: Direction of induced current

Controlled variable: The magnet used **OR** the conducting loop used **OR** the orientation of the magnet

7C Generators and alternators

Theory review questions

1 D

2 **a** Y **b** X **c** X **d** Y

3 B

4 **a** X **b** W

5 A

6

AC alternator	B
DC generator	A
Slip rings	B
Split ring commutator	A
DC output	A
AC output	B

Exam-style questions

This lesson

7 a $f = \frac{1}{T} = \frac{1}{20 \times 10^{-3}}$ (1 MARK)

$f = 50$ Hz (1 MARK)

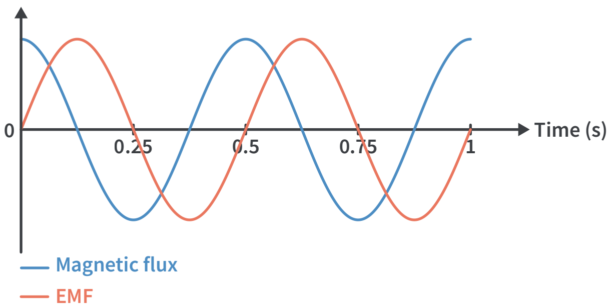
b [The maximum magnitude of EMF will occur when the coil is parallel to the magnetic field (horizontal).[1]][At this position the rate of change of flux is a maximum.[2]]

- I have explicitly addressed the orientation at which the magnitude of EMF is a maximum.[1]
- I have used the relevant theory: the relationship between EMF and rate of change of flux.[2]

c

Suggested change	Effect on EMF amplitude
Decrease the period of rotation of the coil.	Increase
Decrease the strength of the permanent magnets.	Decrease
Increase the number of turns in the coil.	Increase
Increase the area of the coil.	Increase

8 a



I have shown the magnitude of the magnetic flux to be a maximum at $t = 0$ s.

I have shown the magnetic flux to vary sinusoidally and complete one full cycle in 0.5 seconds.

I have shown the EMF to be zero at $t = 0$ s.

I have shown the EMF to vary sinusoidally.

I have shown the EMF to be a maximum one quarter of a cycle (0.125 seconds) later than the magnetic flux.

I have shown two full cycles for both the magnetic flux and the EMF.

b $\Phi_B = B_\perp A = 0.090 \times (0.30 \times 0.50)$ (1 MARK)

$\Phi_B = 1.35 \times 10^{-2} = 1.4 \times 10^{-2}$ Wb (1 MARK)

c $f = \frac{1}{T} = \frac{1}{0.50} = 2.0$ Hz

d $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 20 \times \frac{1.35 \times 10^{-2}}{\frac{0.50}{4}}$ (1 MARK)

$\varepsilon = 2.2$ V (1 MARK)

e [Slip rings allow the coil in an alternator to rotate while maintaining contact with an external circuit[1]][so that the alternating EMF induced in the coil is passed to the output as AC electricity.[2]]

I have explicitly addressed the function of slip rings.[1]

I have explicitly addressed the output of alternators.[2]

9 a $f = \frac{1}{T}$ $\therefore T = \frac{1}{10} = 0.10$ s (1 MARK)

$\Delta t = \frac{T}{4} = \frac{0.10}{4} = 0.025$ s

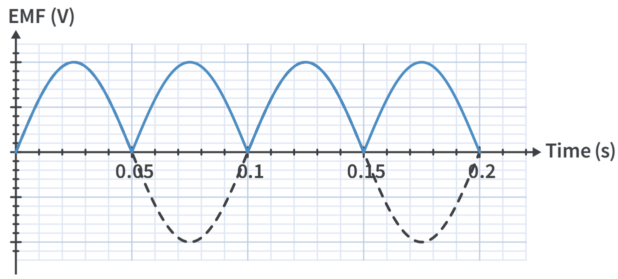
$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$ $\therefore 1.6 = 5 \times \frac{\Delta\Phi_B}{0.025}$ (1 MARK)

$\Phi_B = 8.0 \times 10^{-3}$ Wb (1 MARK)

$\Phi_B = B_\perp A$ $\therefore 8.0 \times 10^{-3} = 8.0 \times 10^{-3} \times L^2$

$L = 1.0$ m $= 1.0 \times 10^2$ cm (1 MARK)

b



I have drawn a solid line which inverts either the positive or the negative EMF values of the original graph.

Previous lessons

10 a When $m = 60.0$ g, $\Delta x = 5.88$ cm.

$F_A = k_A\Delta x = 3.00 \times 5.88 \times 10^{-2}$ (1 MARK)

$F_A = 0.1764 = 0.176$ N (1 MARK)

b The sum of the two spring forces balances the force due to gravity. When $m = 60.0$ g:

$F_A + F_B = F_g$ $\therefore 0.1764 + F_B = mg$

$0.1764 + F_B = 60.0 \times 10^{-3} \times 9.8$ (1 MARK)

$F_B = 0.4116 = 0.412$ N (1 MARK)

c When $m = 60.0$ g:

$F_B = k_B\Delta x$ $\therefore 0.4116 = k_B \times 5.88 \times 10^{-2}$ (1 MARK)

$k_B = 7.00$ N m^{-1} (1 MARK)

d $SPE = \frac{1}{2}k_B(\Delta x)^2 = \frac{1}{2} \times 7.00 \times (5.00 \times 10^{-2})^2$ (1 MARK)

$SPE = 8.75 \times 10^{-3}$ J (1 MARK)

11 a There are approximately 22 squares (between 20 and 24 is acceptable) beneath the graph between R_E and 20×10^6 m.

Area of each square =
$(1.0 \text{ N kg}^{-1}) \times (2.0 \times 10^6 \text{ m}) = 2.0 \times 10^6 \text{ J kg}^{-1}$ (1 MARK)

$\Delta GPE = 22 \times 2.0 \times 10^6 \times 1300$ (1 MARK)

$\Delta GPE = 5.7 \times 10^{10}$ J (1 MARK)

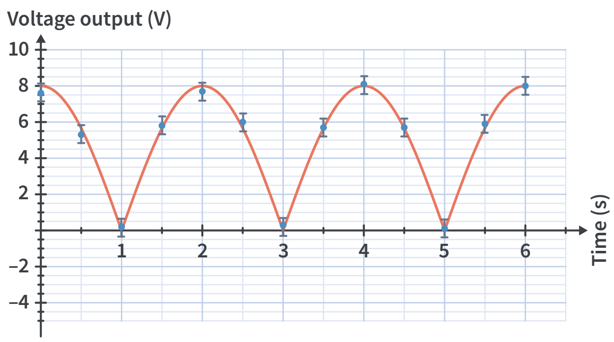
b The area under the graph between the centre and the surface of Earth is a triangle.

$\Delta GPE = \frac{1}{2} \times 6.37 \times 10^6 \times 9.8 \times 1300$ (1 MARK)

$\Delta GPE = 4.1 \times 10^{10}$ J (1 MARK)

Key science skills

12 a



- I have labelled the horizontal axis and included units.
- I have labelled the vertical axis and included units.
- I have included an appropriate and consistent scale on the axes so that the data takes up more than half of each axis.
- I have plotted each data point.
- I have drawn correctly sized uncertainty bars.
- I have drawn a curve of best fit which passes through all uncertainty bars.

b The time from zero voltage to peak voltage occurs over one-quarter rotation.

Hence from the graph: $T = 4.0$ s (1 MARK)

$f = \frac{1}{T} = \frac{1}{4.0} = 0.25$ Hz (1 MARK)

c [The coil is connected via a split ring commutator[1]][because the output voltage has a constant direction (all voltage values are positive).[2]]

- I have explicitly addressed the connection between the coil and the output.[1]
- I have used the relevant theory: relationship between generator voltage direction and connection type.[2]

Chapter 7 Review

Section A

1 B **2** D **3** C **4** A **5** D

Section B

6 $T = 1.5$ s, amplitude = 4.0 V, $f = \frac{1}{T} = \frac{1}{1.5} = 0.67$ Hz.

7

Change	Impact on peak EMF (increase, decrease or no change)
Increase the period of the generator coil's rotations.	Decrease
Increase the magnetic field strength.	Increase
Increase the number of turns in the generator coil.	Increase
Increase the resistance of the phone charger circuit.	No change
Increase the cross-sectional area of the generator coil.	Increase

8 **a** $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 4 \times \frac{(1.6 - 0.4)}{0.5} = 9.6$ V (1 MARK)

$V = RI \therefore 9.6 = 0.80 \times I$ (1 MARK)

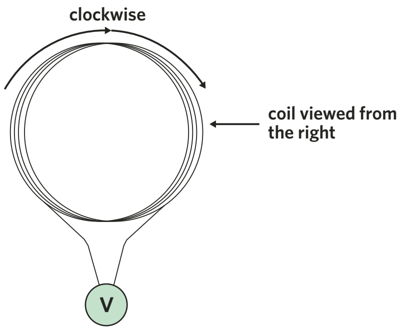
$I = 12$ A (1 MARK)

b EMF is a maximum when the rate of change of flux is a maximum (when the gradient has a maximum magnitude).

The gradient has a maximum positive value at 0.25 s, 1.25 s, and 2.25 s (1 MARK)

The gradient has a maximum negative value at 0.75 s, 1.75 s, and 2.75 s (1 MARK)

c [As the magnet approaches the coil, the magnetic flux through the coil is increasing[1]][to the right.[2]][By Lenz's law the induced current would oppose this change in flux[3]][by creating a magnetic field to the left.[4]][Using the right-hand coil rule,[5]][the induced current when observed from the right is clockwise.[6]]



- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]
- I have explicitly addressed the direction of magnetic flux.[2]
- I have used the relevant theory: Lenz's law.[3]
- I have explicitly addressed the direction of the induced magnetic field.[4]
- I have explicitly referenced the right-hand coil rule.[5]
- I have explicitly stated the direction of the induced current or shown it on a diagram.[6]

d Position 1: (0), 2.0 s (1 MARK)

Position 2: 0.5, 1.5, 2.5 s (1 MARK)

Position 3: 1.0, 3.0 s (1 MARK)

9 [The flux through the square coil is zero[1]][because the magnetic field produced by the solenoid is parallel to the plane of the loop.[2]]

- I have explicitly stated the flux through the coil.[1]
- I have used the relevant theory: effect of angle on flux.[2]

10 **a** $\Phi_B = BA \therefore 0.15 = B \times 0.20 \times 0.30$ (1 MARK)

$B = 2.5$ T **OR** Wb m^{-2} (2 MARKS)

b $T = \frac{1}{f} = \frac{1}{8.0} = 0.125$ s

For a quarter rotation $\Delta t = \frac{0.125}{4} = 3.13 \times 10^{-2}$ s (1 MARK)

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 5 \times \frac{0.15}{3.13 \times 10^{-2}}$ (1 MARK)

$\varepsilon = 24$ V (1 MARK)

c [The magnetic flux through the coil in the horizontal position begins as zero[1]][and then increases to a maximum of 0.15 Wb in the vertical position.[2]][It then returns to zero in the horizontal position[3]][before increasing to the 0.15 Wb maximum through the other side of the coil in the vertical position.[4]][After one revolution it will return to having zero magnetic flux through the coil in the horizontal position.[5]]

- I have explicitly addressed the initial position.[1]
- I have explicitly addressed the vertical position.[2]
- I have explicitly addressed the second horizontal position.[3]
- I have explicitly addressed the second vertical position.[4]
- I have explicitly addressed the final position.[5]

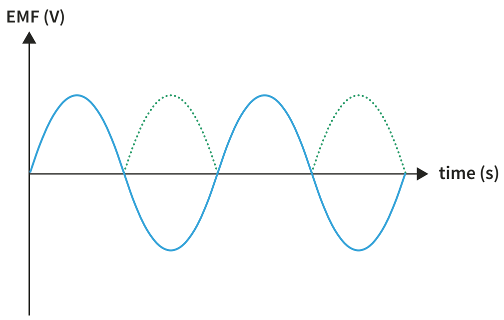
d [The maximum EMF occurs when the coil is in the horizontal position[1]][because this is when the rate of change of magnetic flux is greatest[2]][which creates the greatest EMF according to Faraday's law $\left(\varepsilon = N\dfrac{\Delta\Phi_B}{\Delta t}\right)$.[3]]

- I have explicitly addressed which orientation(s) create the maximum EMF.[1]
- I have used the relevant theory: rate of change of flux.[2]
- I have used the relevant theory: Faraday's law.[3]

e [The split ring commutator should be replaced with slip rings.[1]] [The slip rings maintain a constant connection between the external circuit and the rotating coil which produces an alternating current as it is rotated.[2]]

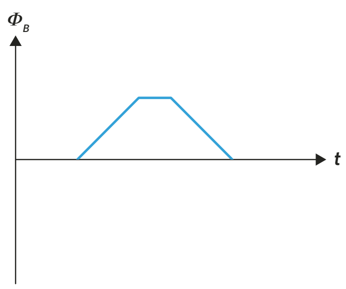
- I have explicitly addressed how to convert to an AC alternator.[1]
- I have used the relevant theory: slip rings.[2]

f



- I have drawn a sinusoidal graph which has the same amplitude as the DC graph.
- I have drawn a sinusoidal graph which has the same period as the DC graph.

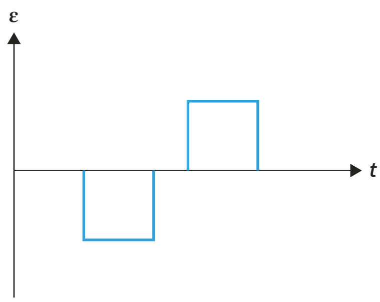
11 a



A negative version of this graph (flipped upside down) is also correct.

- I have drawn a positively sloped straight line.
- I have drawn a straight horizontal line.
- I have drawn a negatively sloped straight line.

b



A negative version of this graph (flipped upside down) is also correct.

- I have drawn a negative EMF with constant value.
- I have included a period of zero EMF.
- I have drawn a positive EMF with constant value and duration equal to the negative section.

c [As the loop enters the magnetic field, the flux through the coil is increasing[1]][upwards.[2]][By Lenz's law the induced current would oppose this change in flux[3]][by creating a magnetic field directed downwards.[4]][Using the right-hand coil rule,[5]][the induced current flows from *Y* to *X* through the voltmeter.[6]]

- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]
- I have explicitly addressed the direction of magnetic flux.[2]
- I have used the relevant theory: Lenz's law.[3]
- I have explicitly addressed the direction of the induced magnetic field.[4]
- I have explicitly referenced the right-hand coil rule.[5]
- I have explicitly stated the direction of the induced current through the voltmeter.[6]

8A Electricity recap

Theory review questions

1 C **2** A **3** B **4** B **5** D

Exam-style questions

This lesson

6 $R_T = 300 + 2.00 \times 10^3 + 1.00 \times 10^3 + 500 = 3800 = 3.80 \times 10^3\ \Omega$

7 $V = RI \ \therefore 9.0 = R \times 5.0$

$R = 1.8\ \Omega$

8 a $V = RI \ \therefore 10 = 200 \times I$

$I = 0.050$ A

b $P = \frac{V^2}{R} = \frac{10^2}{200} = 0.50$ W

OR

$P = VI = 10 \times 0.050 = 0.50$ W

OR

$P = I^2R = 0.050^2 \times 200 = 0.50$ W

9 $P = I^2R = 10^2 \times 100 = 1.00 \times 10^4$ W (1 MARK)

$\Delta E = P\Delta t = 1.00 \times 10^4 \times 10 = 1.0 \times 10^5$ J (1 MARK)

10 $P = \frac{V^2}{R} \ \therefore 30 = \frac{V^2}{200}$ (1 MARK)

$V = 77$ V (1 MARK)

11 Consider the resistor, since it is the only component for which we know the resistance.

$V_R = V_{sup} - V_{light} = 7 - 5 = 2$ V

$V_R = RI \ \therefore 2 = I \times 2$

$I = 1$ A (1 MARK)

The current in the light globe is the same, since it is a series circuit.

$P_{light} = V_{light}I = 5 \times 1 = 5$ W (1 MARK)

12 a $R_T = 2.0 + 2.0 + 12.0 = 16.0\ \Omega$

$P = \frac{{V_{sup}}^2}{R_T} = \frac{50.0^2}{16.0}$ (1 MARK)

$P = 156$ W (1 MARK)

b $R_T = 2.0 + 2.0 + 12.0 = 16.0\ \Omega$

$V = R_TI \ \therefore 50.0 = 16.0 \times I$

$I = 3.125$ A (1 MARK)

$V = RI = 12.0 \times 3.125 = 37.5$ V (1 MARK)

c $R = 2.0 + 2.0 = 4.0\ \Omega$

$I = 3.125$ A from part **b**

$P = I^2R = 3.125^2 \times 4.0$ (1 MARK)

$P = 39.1$ W (1 MARK)

13 $P_{sup} = \frac{\Delta E}{\Delta t} = \frac{12}{4} = 3$ W (1 MARK)

$P_{sup} = IV_{sup} \ \therefore 3 = I \times 3$

$I = 1$ A (1 MARK)

$V_{sup} = IR_T \ \therefore 3 = 1 \times (2 + R_2)$

$R_2 = 1\ \Omega$ (1 MARK)

OR

$P = \frac{\Delta E}{\Delta t} = \frac{12}{4} = 3$ W (1 MARK)

$P_{sup} = \frac{{V_{sup}}^2}{R_T} \ \therefore 3 = \frac{3^2}{2 + R_2}$ (1 MARK)

$R_2 = 1\ \Omega$ (1 MARK)

Previous lessons

14 a $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = GPE_f \ \therefore \frac{1}{2}k(\Delta x)^2 = mgh$ (1 MARK)

$\frac{1}{2} \times 200 \times (\Delta x)^2 = 0.1 \times 9.8 \times 0.25$ (1 MARK)

$\Delta x = 0.05$ m

b $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = KE_f \ \therefore \frac{1}{2}k(\Delta x)^2 = \frac{1}{2}mv^2$

$\frac{1}{2} \times 200 \times (0.05)^2 = \frac{1}{2} \times 0.1 \times v^2$ (1 MARK)

$v = 2$ m s^{-1} (1 MARK)

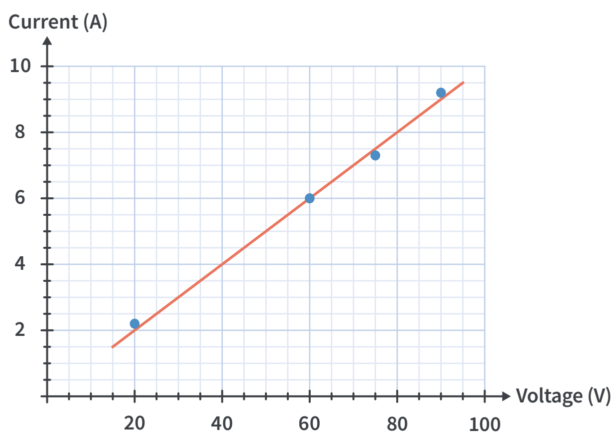
15 $F = \frac{kq_1q_2}{r^2} = \frac{8.99 \times 10^9 \times 5.0 \times 10^{-15} \times 1.6 \times 10^{-19}}{10^2} = 7.19 \times 10^{-26}$ N (1 MARK)

$F = ma \ \therefore 7.192 \times 10^{-26} = 9.1 \times 10^{-31} \times a$ (1 MARK)

$a = 7.9 \times 10^4$ m s^{-2} (1 MARK)

Key science skills

16 a



I have drawn the horizontal axis as the independent variable, and included correct labels and units.

I have drawn the vertical axis as the dependent variable, and included correct labels and units.

I have used an appropriate and consistent scale so that the data takes up the majority of the graph space.

I have plotted each point of data.

b $gradient = \frac{rise}{run} = \frac{I}{V} = \frac{1}{R}$

$R = \frac{1}{gradient}$ (1 MARK)

Using any two points on the line of best fit:

$gradient = \frac{8.0-2.0}{80-20} = 0.10 \therefore R = \frac{1}{gradient} = \frac{1}{0.10} = 10\ \Omega$ (1 MARK)

A range of answers is acceptable, depending on the line of best fit that was drawn.

8B Transformers and comparing AC and DC power

Theory review questions

1 C **2** A **3** B **4** C

5 D **6** B

Exam-style questions

This lesson

7 D. $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{345}{15} = \frac{23}{1}$

8 B. Batteries provide a constant DC voltage, so the required voltage is going to be equal to the V_{RMS} of the AC supply.

9 $\frac{N_1}{N_2} = \frac{I_2}{I_1} \therefore \frac{200}{1200} = \frac{13.5}{I} \therefore I = 81.0\ A_{RMS}$

10 D. The peak is 3.5 cm above the horizontal axis, so $V_{peak} = 3.5 \times 3.0 = 10.5$ V.

$V_{RMS} = \frac{1}{\sqrt{2}}V_{peak} = \frac{1}{\sqrt{2}} \times 10.5 = 7.4$ V

11 a $\frac{N_1}{N_2} = \frac{V_1}{V_2} \therefore \frac{500}{4000} = \frac{2.0}{V_2} \therefore V_2 = 16\ V_{RMS}$

b $V_{RMS} = \frac{1}{\sqrt{2}}V_{peak} \therefore 16 = \frac{1}{\sqrt{2}} \times V_{peak}$

$V_{peak} = 23$ V

c $P = \frac{V^2}{R} = \frac{16^2}{1000}$ (1 MARK)

$P = 0.26$ W (1 MARK)

d [There will be an induced voltage in the secondary coil, and hence a current in the resistor, only when there is a change in magnetic flux through the secondary coil.[1]][When the switch is closed, there is an increase in the current in the primary coil which results in a change in the flux in the secondary coil.[2]][When the switch remains closed there is no change in the current in the primary coil and so no change in the flux.[3]]

I have used the relevant theory: Faraday's law.[1]

I have explicitly addressed the current and the flux as the switch closes.[2]

I have explicitly addressed the current and the flux as the switch remains closed.[3]

12 a Use RMS values: $\frac{N_1}{N_2} = \frac{V_1}{V_2} \therefore \frac{15}{1} = \frac{V_1}{16.0}$

$V_1 = 240\ V_{RMS}$ (1 MARK)

Convert to peak values: $V_{RMS} = \frac{1}{\sqrt{2}}V_{peak} \quad \therefore 240 = \frac{1}{\sqrt{2}} \times V_{peak}$

$V_{peak} = 339$ V (1 MARK)

b Use RMS values for all calculations.

On the secondary side: $V_2 = RI_2 \therefore 20.0 = 10 \times I_2$

$I_2 = 2.0\ A_{RMS}$ (1 MARK)

$\frac{N_1}{N_2} = \frac{I_2}{I_1} \therefore \frac{15}{1} = \frac{2.0}{I_1}$

$I_1 = 0.13\ A_{RMS}$ (1 MARK)

13 Calculate the voltage in the amplifier.

$P = \frac{V_2^{\ 2}}{R} \therefore 144 = \frac{V_2^{\ 2}}{36}$

$V_2 = 72$ V (1 MARK)

$\frac{N_1}{N_2} = \frac{V_1}{V_2} \therefore \frac{500}{N_2} = \frac{18}{72}$ (1 MARK)

$N_2 = 2000$ turns (1 MARK)

Previous lessons

14 [Einstein's first postulate is that the laws of physics are the same in any inertial reference frame.[1]][This concept is consistent with classical physics.[2]]

I have stated Einstein's first postulate.[1]

I have explicitly addressed whether the concept differs from classical physics.[2]

15 D. The attractive forces that the central positive charge experiences due to the top-right and bottom-left negative charges are balanced. The attractive and repulsive forces due to the top-left and bottom-right negative charges both act diagonally up and left.

Key science skills

16 D. The effects of individual deviations in a measurement from a true value are reduced when the average is calculated due to the division by the number of measurements. Furthermore, due to the random nature of random errors (sometimes leading to a greater measured value and sometimes a smaller measured value), when the average is taken from multiple measurements, the errors are more likely to offset each other when more measurements are taken.

8C Transmission of power

Theory review questions

1 D **2** A **3** B **4** D

Exam-style questions

This lesson

5 a $P_{loss} = I_{line}^2 R_{line} = 125^2 \times 2.0$ (1 MARK)

$P_{loss} = 31\,250 \text{ W} = 31 \text{ kW}$ (1 MARK)

b The power in transformer T_1 must be constant. The new voltage in the secondary side is smaller by a factor of 10. Therefore the new current is greater by a factor of 10. (1 MARK)

$P_{loss} = I_{line}^2 R_{line}$ $\therefore$ Power loss is greater by a factor of $10^2 = 100$. (1 MARK)

OR

The power in transformer T_1 must be constant.

$P = VI$ $\therefore 25 \times 10^6 = 20 \times 10^3 \times I$ $\therefore I = 1250$ A (1 MARK)

$P_{loss} = I_{line}^2 R_{line} = 1250^2 \times 2.0 = 3.125 \times 10^6$ W

Power loss factor increase $= \dfrac{3.125 \times 10^6}{31\,250} = 100$ (1 MARK)

6 a Consider the light tower:
$P_{load} = V_{load} I_{load}$ $\therefore 720 = 240 \times I_{load}$ $\therefore I_{load} = 3.00$ A (1 MARK)

Circuit is a series circuit, so the current in the line is the same as the current in the light tower.

$P_{loss} = I_{line}^2 R_{line} = 3.00^2 \times 10$ (1 MARK)

$P_{loss} = 90$ W (1 MARK)

b $V_{sup} = V_{drop} + V_{load} = I_{line} R_{line} + V_{load} = 3.00 \times 10 + 240$ (1 MARK)

$V_{in} = V_{sup} = 270 \text{ V}_{RMS}$ (1 MARK)

OR

$P_{sup} = P_{loss} + P_{load} = 90 + 720 = 810$ W (1 MARK)

$P_{sup} = V_{sup} I_{sup}$ and the current in the power supply is the same as the current in the light tower.

$810 = V_{sup} \times 3.00$ $\therefore V_{in} = V_{sup} = 270$ V (1 MARK)

c Since the light tower is operating as normal, the current in the light is the same as in part **a**. $\therefore I_{load} = 3.00$ A

Consider the transformer: $\dfrac{N_1}{N_2} = \dfrac{I_{load}}{I_{line}}$ $\therefore \dfrac{10}{1} = \dfrac{3.00}{I_{line}}$

$I_{line} = 0.300$ A (1 MARK)

$P_{loss} = I_{line}^2 R_{line} = 0.300^2 \times 10$ (1 MARK)

$P_{loss} = 0.90$ W (1 MARK)

7 a $P = VI = 4.0 \times 2.50 = 10$ W

b The circuit is a single series circuit with a single current flowing
$\therefore V_{sup} = IR_{total}$

$5.0 = I \times (0.80 + 1.6)$ (1 MARK)

$I = 2.08 = 2.1$ A (1 MARK)

c [The pump will not operate correctly[1]][since the motor does not receive enough current.[2]][The current delivered to the motor is only 2.1 A (from part **b**) but it requires 2.50 A to operate correctly.[3]]

- I have explicitly addressed whether the pump operates correctly.[1]
- I have related my answer to the context of the question.[2]
- I have used data to support my answer.[3]

d [One way would be to install a step-up transformer near the power supply and a step-down transformer near the load in order to increase the transmission voltage and reduce the current in the lines.[1]][This would result in a reduced power loss since $P_{loss} = I^2 R$.[2]][A second method is to reduce the resistance of the connecting wires.[3]][Again this would result in a reduced power loss according to $P_{loss} = I^2 R$.[4]]

- I have explicitly addressed one method of reducing power loss.[1]
- I have related this change to the power loss equation.[2]
- I have explicitly addressed one method of reducing power loss.[3]
- I have related this change to the power loss equation.[4]

8 a [The globe would receive less than 3.0 V (**OR** 6.0 W)[1]][since there is a resistance in the transmission lines[2]][which causes a voltage drop (**OR** power loss) in the lines.[3]]

- I have explicitly addressed the reason the globe does not glow as brightly as expected.[1]
- I have explicitly addressed the resistance in the transmission lines.[2]
- I have used the relevant theory: voltage drop/power loss in transmission lines.[3]

b Consider the light globe:
$P_{load} = V_{load} I_{load}$ $\therefore 6.0 = 3.0 \times I_{load}$ $\therefore I_{load} = 2.0$ A (1 MARK)

Circuit is a series circuit, so the current in the line is the same as the current in the globe.

$V_{drop} = I_{line} R_{line} = 2.0 \times (1.5 + 1.5) = 6.0$ V (1 MARK)

$V_{sup} = V_{drop} + V_{load} = 6.0 + 3.0 = 9.0$ V (1 MARK)

c $I_{line} = 2.0$ A as calculated in part **b**

$P_{loss} = I_{line}^2 R_{line} = 2.0^2 \times (1.5 + 1.5)$ (1 MARK)

$P_{loss} = 12$ W (1 MARK)

d [AC is often used for long-distance power transmission because the alternative, constant DC power, cannot use transformers[1]][which help to reduce power loss by transmitting power at a lower current.[2]]

- I have used the relevant theory: transformers require changing current.[1]
- I have used the relevant theory: transformers used to reduce power loss.[2]
- I have explicitly addressed the question.

e $I_{load} = 2.0$ A as calculated in part **b**

Use transformer ratios to find the current in the line.

$\frac{N_1}{N_2} = \frac{I_{load}}{I_{line}}$ $\therefore \frac{5}{1} = \frac{2.0}{I_{line}}$ $\therefore I_{line} = 0.40$ A (1 MARK)

$P_{loss} = I_{line}^2 R_{line} = 0.40^2 \times (1.5 + 1.5)$ (1 MARK)

$P_{loss} = 0.48$ W (1 MARK)

f $P_{sup} = P_{loss} + P_{load} = 0.48 + 6.0 = 6.48$ W (1 MARK)

$I_{sup} = I_{line} = 0.40$ A, since the power supply is part of the same series circuit as the transmission lines.

$P_{sup} = V_{sup} I_{sup}$ $\therefore 6.48 = V_{sup} \times 0.40$ (1 MARK)

$V_{sup} = 16.2 = 16$ V (1 MARK)

OR

Consider the transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_{load}}$ where V_1 is the voltage across the primary side of the transformer. $\therefore \frac{5}{1} = \frac{V_1}{3.0}$ $\therefore V_1 = 15$ V (1 MARK)

$V_{sup} = V_{drop} + V_1 = I_{line} R_{line} + V_1 = 0.40 \times (1.5 + 1.5) + 15$ (1 MARK)

$V_{sup} = 16.2 = 16$ V (1 MARK)

Previous lessons

9 $L = 4.00 - 0.040 = 3.96$ m

$L = \frac{L_0}{\gamma}$ $\therefore 3.96 = \frac{4.00}{\gamma}$ $\therefore \gamma = 1.010$ (1 MARK)

$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ $\therefore v = c\sqrt{1 - \frac{1}{\gamma^2}}$

$v = c\sqrt{1 - \frac{1}{1.010^2}}$ (1 MARK)

$v = 0.141c$ (1 MARK)

10 a $F = qvB = 1.6 \times 10^{-19} \times 2.5 \times 10^{7} \times 8.0 \times 10^{-2}$ (1 MARK)

$F = 3.2 \times 10^{-13}$ N (1 MARK)

b [The electrons follow a circular path[1]][since the force acting on them is always at right angles to their direction of motion (as is the case for a centripetal force).[2]]

- I have explicitly addressed the path of the electrons.[1]
- I have used the relevant theory: direction of centripetal forces.[2]

Key science skills

11 [The results are not valid[1]][because there is more than one independent variable in this experiment.[2]][For this experiment to be valid, the transformer ratio should be the only independent variable but the specified power of the light globe has been changed too.[3]]

- I have explicitly addressed the validity of the results.[1]
- I have used the relevant theory: experimental validity and independent variables.[2]
- I have related my answer to the context of the question.[3]

Chapter 8 Review

Section A

1 B **2** D **3** C **4** B **5** A

Section B

6 a $R_T = R_1 + R_2 = 2.0 + 3.0 = 5.0\ \Omega$

b $V = RI$ $\therefore 9.0 = 5.0 \times I$ (1 MARK)

$I = 1.8$ A (1 MARK)

c $V_{drop} = IR = 2.0 \times 1.8 = 3.6$ V

d $P_{loss} = I^2 R = 1.8^2 \times 3.0 = 9.7$ W

7 a $9.0 + 9.0 = 18.0$ V

b 9.0 V

c $V_{RMS} = V_{peak} \times \frac{1}{\sqrt{2}} = 9.0 \times \frac{1}{\sqrt{2}} = 6.4\ V_{RMS}$

8 a $P_{loss} = I_{line}{}^2 R_{line} = 2.5^2 \times 4.0$ (1 MARK)

$P_{loss} = 25$ W (1 MARK)

b $\frac{I_2}{I_1} = \frac{N_1}{N_2}$ $\therefore \frac{I_2}{2.5} = \frac{3}{1}$

$I_2 = 7.5$ A (1 MARK)

$P_{charger} = VI = 5.0 \times 7.5 = 37.5 = 38$ W (1 MARK)

c $P_{total} = P_{charger} + P_{loss}$ (1 MARK)

$P_{total} = 37.5 + 25 = 63$ W (1 MARK)

d $V_{drop} = I_{line} R_{line} = 2.5 \times 4 = 10$ V (1 MARK)

$V_{transformer\ input} = 5.0 \times 3 = 15$ V

$V_{output} = V_{drop} + V_{transformer\ input} = 10 + 15 = 25$ V (1 MARK)

e A current of 7.5 A (calculated in part **b**) must still flow through the charger for it to operate correctly.

$\frac{I_2}{I_1} = \frac{N_1}{N_2}$ $\therefore \frac{7.5}{I_1} = \frac{6}{1}$

$I_{line} = I_1 = 1.25$ A (1 MARK)

$P_{loss} = I_{line}{}^2 R_{line} = 1.25^2 \times 4.0 = 6.3$ W (1 MARK)

9 [Unlike DC, AC power can utilise transformers to reduce power loss.[1]][Transformers allow for transmission at a higher (stepped-up) voltage and a reduced current.[2]][As power loss is proportional to the square of current by $P_{loss} = I_{line}{}^2 R_{line}$, this results in reduced power loss during long distance transmission compared to DC.[3]]

- I have explicitly addressed why AC is prefered.[1]
- I have used the relevant theory: transformers.[2]
- I have used the relevant theory: the relationship between power loss and current.[3]

10 a $\frac{V_1}{V_2} = \frac{N_1}{N_2} \therefore \frac{12000}{300} = \frac{N_1}{50}$ (1 MARK)

$N_1 = 2000$ turns (1 MARK)

b Ratio of T_1 doubles → output voltage doubles → current in transmission lines halves.

$P_{new\ loss} = \left(\frac{1}{2} I_{line}\right)^2 R_{line}$ (1 MARK)

$P_{new\ loss} = \frac{1}{4} \times I_{line}{}^2 R_{line} = \frac{1}{4} \times P_{old\ loss}$ (1 MARK)

c [A battery produces constant DC power which cannot be transmitted through a transformer.[1]][A transformer relies on a changing magnetic field produced by the primary coil to induce a current in the secondary coil.[2]][The constant current from a battery produces a constant magnetic field so there is no induced current in the secondary coil.[3]]

- I have explicitly addressed why DC would be ineffective.[1]
- I have used the relevant theory: transformer operation.[2]
- I have used the relevant theory: DC power.[3]

11 a $P = VI \therefore 15.0 \times 10^3 = 250 \times I$ (1 MARK)

$I = 60.0$ A (1 MARK)

b Step-down transformer: $\frac{I_2}{I_{line}} = \frac{V_1}{V_2} \therefore \frac{60.0}{I_{line}} = \frac{11.0 \times 10^3}{250}$

$I_{line} = 1.364$ A (1 MARK)

$P_{loss} = I_{line}{}^2 R_{line} = 1.364^2 \times 25.0$ (1 MARK)

$P_{loss} = 46.5$ W (1 MARK)

c Consider the series circuit consisting of the output of T_1 (the step-up transformer), the transmission lines, and the input to T_2 (the step-down transformer).

$V_{output\ T1} = V_{input\ T2} + V_{drop}$

$V_{output\ T1} = V_{input\ T2} + I_{line} R_{line} = 11.0 \times 10^3 + 1.364 \times 25.0$ (1 MARK)

$V_{output\ T1} = 1.103 \times 10^4$ V (1 MARK)

d Step-up transformer: $\frac{N_1}{N_2} = \frac{1}{40} = \frac{25}{N_2}$

$N_2 = 1000$ turns

e $P_{total} = P_{home} + P_{loss} = 15.0 \times 10^3 + 46.5$ (1 MARK)

$P_{total} = 1.505 \times 10^4$ W (1 MARK)

OR

Power output of plant is equal to power in step-up transformer.

$P = V_{output\ T1} I_{line} = 1.103 \times 10^4 \times 1.364$ (1 MARK)

$P = 1.505 \times 10^4$ W (1 MARK)

12 a $P = VI = 40\,000 \times 10.0 = 4.00 \times 10^5$ W

b $P_{loss} = I_{line}{}^2 R_{line} \therefore 7000 = 10.0^2 \times R_{line}$ (1 MARK)

$R_{line} = 70.0\ \Omega$ (1 MARK)

c $\frac{I_2}{I_1} = \frac{V_1}{V_2} \therefore \frac{I_2}{I_1} = \frac{39\,300}{240}$ (1 MARK)

$\frac{I_2}{I_1} = 164$ (1 MARK)

13 a $V_{peak} = \sqrt{2} \times V_{RMS} = \sqrt{2} \times 200 = 283\ V_{peak}$

b [200 V DC will deliver the same average power as 200 V_{RMS} AC.[1]][Root-mean-square is a way of measuring AC currents that gives the DC equivalent needed to produce the same average power.[2]]

- I have explicitly stated the equivalent DC voltage.[1]
- I have used the relevant theory: root-mean-square.[2]

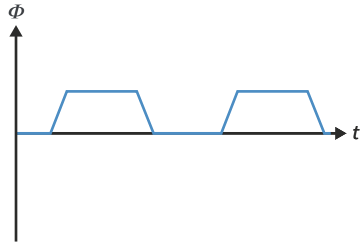
Unit 3, AOS 2 Review

Section A

1 C **2** B **3** B **4** A **5** A

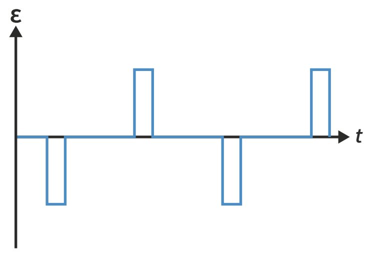
Section B

6 a



- I have correctly labelled the axes.
- I have drawn the appropriate graph.
- I have drawn two repetitions of the same shape.

b



- I have correctly labelled the axes.
- I have drawn the appropriate graph.
- I have drawn two repetitions of the same shape.

c $\Delta\Phi_B = \Delta B_{\perp} A = 0.500 \times 0.15 \times 0.25 - 0 = 1.875 \times 10^{-2}$ Wb

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 25 \times \frac{1.875 \times 10^{-2}}{0.10}$ (1 MARK)

$\varepsilon = 4.7$ V (1 MARK)

d [When viewed from the north pole, the magnetic flux through the loop is increasing[1]][away from the pole (into the page).[2]][By Lenz's law, the induced magnetic field will oppose this change in flux,[3]][so it will be directed towards the pole (out of the page).[4]] [Using the right-hand coil rule,[5]][the induced current will flow anticlockwise when viewed from the north pole.[6]]

- I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]
- I have explicitly addressed the direction of magnetic flux.[2]
- I have used the relevant theory: Lenz's law.[3]
- I have explicitly addressed the direction of the induced magnetic field.[4]
- I have explicitly referenced the right-hand coil rule.[5]
- I have explicitly stated the direction of the induced current when viewed from the north pole.[6]

7 a [Slip rings act as a constant connection between the generator's coil and the external circuit.[1]][This causes the alternating current produced in the coil during rotation to be transferred to the external circuit as AC power.[2]]

- I have explicitly stated how slip rings work.[1]
- I have explicitly explained the function of slip rings.[2]

b $\frac{I_2}{I_1} = \frac{N_1}{N_2} \therefore \frac{I_2}{3.5} = \frac{1}{10}$

$I_2 = 0.35$ A (1 MARK)

$P_{loss} = I^2_{line} R_{line} = 0.35^2 \times 3.5 = 0.43$ W (1 MARK)

c [The farmer could replace the slip ring with a split ring commutator.[1]][The split rings would contact alternate sides of the generator's coil every half rotation, acting to rectify the AC output to DC.[2]]

- I have identified how to convert an AC generator to DC.[1]
- I have used the theory: split-ring commutator.[2]

8 [No power could be transmitted through the transformer.[1]][The transformer can function with AC as the changing magnetic field induces a current in the secondary coil, which is not possible with constant DC.[2]]

- I have stated that no power transmission can occur.[1]
- I have used the relevant theory: transformers.[2]

9 a $\Phi_B = B_{\perp} A \therefore 7.5 \times 10^{-3} = B_{\perp} \times 7.5 \times 10^{-2} \times 12.5 \times 10^{-2}$ (1 MARK)

$B_{\perp} = 0.80$ T or Wb m^{-2} (2 MARKS)

b $T = \frac{1}{f} = \frac{1}{12} = 8.33 \times 10^{-2}$ s

For a quarter rotation: $\Delta t = \frac{8.33 \times 10^{-2}}{4} = 2.08 \times 10^{-2}$ s (1 MARK)

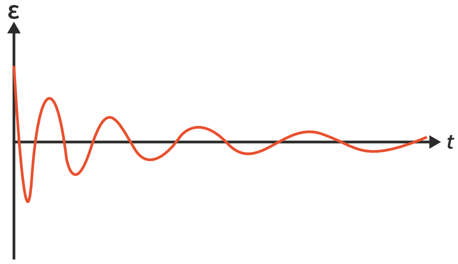
$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 10 \times \frac{7.5 \times 10^{-3}}{2.08 \times 10^{-2}}$ (1 MARK)

$\varepsilon = 3.6$ V (1 MARK)

c [As the coil rotates in the magnetic field, the magnetic flux through the coil was to the right and increasing when viewed from the handle.[1]][Hence the induced current would oppose this change in flux and increase flux to the left by Lenz's law.[2]] [Using the right-hand grip rule, the induced current would be from C to B.[3]]

- I have explicitly addressed the initial change in magnetic flux.[1]
- I have used the relevant theory: Lenz law.[2]
- I have explicitly stated the direction of the induced current.[3]

d



- I have correctly labelled my axes.
- I have drawn an oscillating voltage.
- I have drawn a graph with decreasing amplitude.
- I have drawn a graph with increasing period.

10 a $P_{loss} = I^2_{line} R_{line} = 16.0^2 \times 35.0$ (1 MARK)

$P_{loss} = 8.96 \times 10^3$ W (1 MARK)

b Output of step-up: $\frac{V_1}{V_2} = \frac{N_1}{N_2} \therefore \frac{900}{V_2} = \frac{1}{15}$

$V_2 = 1.35 \times 10^4$ V (1 MARK)

$V_{drop} = I_{line} R_{line} = 16.0 \times 35.0 = 560$ V (1 MARK)

Input of step-down: $V_1 = V_2 - V_{drop} = 1.35 \times 10^4 - 560$

$V_1 = 1.294 \times 10^4$ V (1 MARK)

Output of step-down is the voltage across the lamp:

$\frac{V_1}{V_2} = \frac{N_1}{N_2} \therefore \frac{1.294 \times 10^4}{V_{lamp}} = \frac{15}{1}$

$V_{lamp} = 8.6 \times 10^2$ V (1 MARK)

c Increase the output voltage of the power plant **OR** increase the ratio of secondary to primary coils on the step-up transformer **OR** decrease the ratio of primary to secondary coils on the step-down transformer **OR** use a thicker cable with less resistance.

11 a $P = VI \therefore 18 = 4.5 \times I$

$I = 4.0$ A (1 MARK)

$\frac{I_2}{I_1} = \frac{N_1}{N_2} \therefore \frac{4.0}{I_{line}} = \frac{20}{1}$ (1 MARK)

$I_{line} = 0.20$ A (1 MARK)

b $P_{loss} = I^2_{line} R_{line} = 0.20^2 \times (3.0 + 3.0)$ (1 MARK)

$P_{loss} = 0.24$ W (1 MARK)

REVIEW

c $\frac{V_1}{V_2} = \frac{N_1}{N_2} \therefore \frac{V_1}{4.5} = \frac{20}{1}$

$V_1 = 90$ V (input to T_2) (1 MARK)

$V_{drop} = I_{line} R_{line} = 0.20 \times 6.0 = 1.2$ V (1 MARK)

$V_{output} = V_1 + V_{drop} = 90 + 1.2 = 91.2$ V (1 MARK)

$\frac{V_1}{V_2} = \frac{N_1}{N_2} \therefore \frac{V_{input}}{91.2} = \frac{1}{20}$

$V_{input} = 4.6$ V (1 MARK)

d [Unlike DC, AC power is able to utilise ideal transformers.[1]] [Transformers allow for the transmission of power at a higher (stepped up) voltage and a reduced current.[2]] [As power loss is proportional to the square of current by $P_{loss} = I_{line}^2 R_{line}$, this results in reduced power loss compared to when using DC.[3]] [Therefore, AC is preferred for long-distance power transmission.[4]]

- I have explicitly addressed why AC is prefered.[1]
- I have used the relevant theory: transformers.[2]
- I have used the relevant theory: power loss.[3]
- I have related my answer to the context of the question.[4]

9A Wave fundamentals

Theory review questions

1 C	**2** C	**3** D
4 B	**5** D	**6** A
7 C	**8** C	**9** B

Exam-style questions

This lesson

10 a A. A is the only particle for which displacement increases from 0 cm just after $t = 0$ s.

b $T = 5$ s (1 MARK)

$f = \frac{1}{T} = \frac{1}{5} = 0.2$ Hz (1 MARK)

c $t = \frac{3}{4}T + T$ (1 MARK)

$t = 3.75 + 5 = 8.75$ s (1 MARK)

11 a A: not moving, B: up, C: up, D: down

b Distance = 2.5 cm. Displacement = −2 cm

12 a A: left, B: right, C: right, D: right

b Distance = 5.5 m. Displacement = −0.2 cm

13 [The particle oscillates left and right[1]][at a frequency of 50 Hz.[2]][Its initial position (3 cm from the speaker) is the mean position of the oscillations.[3]]

- I have explicitly addressed the oscillation of the particle.[1]
- I have used the provided data in my answer.[2]
- I have explicitly addressed the initial position of the particle.[3]

14 [Dominique should make the period shorter[1]][as period and frequency are inversely proportional $\left(f = \frac{1}{T}\right)$, and so a smaller value of T will result in a greater value of f.[2]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: the relationship between period and frequency.[2]

15 a Whole spring: displacement-distance graph.

One point: displacement-time graph.

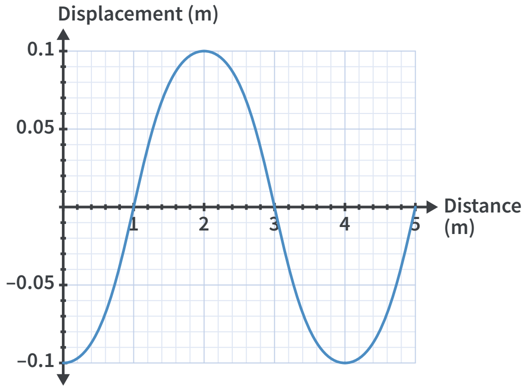
b $A = 0.1$ m

c $\lambda = 4$ m

d $T = 6$ s

e $f = \frac{1}{T} = \frac{1}{6} = 0.167$ Hz

f



- I have plotted a sinusoidal line going through the points: (0, −0.1), (1, 0), (2, 0.1), (3, 0), (4, −0.1), and (5, 0).
- I have used a consistent and appropriate scale on each axis so that the space between each grid line represents a consistent value and the data takes up at least half the space on the axis.
- I have included appropriate units on each axis.

16 a $\lambda = 20$ cm

b $\frac{1}{4}T = 0.20$ (1 MARK)

$f = \frac{1}{T} = \frac{1}{4 \times 0.20} = 1.25$ Hz (1 MARK)

Previous lessons

17 $\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \frac{1}{\sqrt{1 - 0.90^2}} = 2.294$

$L = \frac{L_0}{\gamma} = \frac{4.01 \times 10^{16}}{2.294} = 1.75 \times 10^{16}$ m (1 MARK)

$t = \frac{d}{v} = \frac{1.75 \times 10^{16}}{0.90 \times 3.0 \times 10^8}$ (1 MARK)

$t = 6.47 \times 10^7$ s = 2.1 years (1 MARK)

18 [The coil begins to rotate because forces act on the current-carrying wires WX and YZ in opposite directions which creates a torque (turning effect).[1]][The forces are due to current flowing perpendicular to the magnetic field.[2]][By the right hand palm rule, as the current flows from W to X and the magnetic field is from left to right, the force on the left side of the coil is directed down. Similarly, the force on the right side of the coil is directed upwards.[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: conditions for magnetic force.[2]
- I have used the relevant theory: application of right hand palm rule.[3]
- I have related my answer to the context of the question.

Key science skills

19 [Izzy has more accurate data and Emma has more precise data.[1]][Izzy's average (696.2 nm) is closer than Emma's average (696.8 nm) to the actual wavelength (695 nm).[2]][The range of Emma's measurements (5 nm) is smaller than Izzy's range (17 nm).[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.

9B Wave speed

Theory review questions

1 C	**2** A	**3** B	**4** D
5 A	**6** C	**7** A	**8** C

Exam-style questions

This lesson

9 [The waves are travelling at the same speed after exiting the tank as before entering the tank.[1]][The speed of sound in air is constant as wave speed is dependent solely on the medium in which the wave is propagating.[2]]

I have explicitly addressed the question: compare wave speed before and after tank.[1]

I have used the relevant theory: the dependence of wave speed on the medium.[2]

10 [If period is doubled wavelength will also double.[1]][This is determined from the equation $v = \frac{\lambda}{T}$, which can be expressed as $\lambda = vT$. This shows that wavelength is proportional to period.[2]]

I have explicitly addressed the effect of doubling period on wavelength.[1]

I have used the relevant theory: the wave equation.[2]

11 $\lambda = \frac{v}{f} = \frac{340}{135} = 2.52$ m

12 $\lambda = \frac{v}{f} = \frac{340}{440} = 0.773$ m

13 $v = f\lambda = 1000 \times 0.338 = 338$ m s^{-1}

14 $v = \frac{\lambda}{T} = \frac{4.50}{2.00} = 2.25$ m s^{-1}

15 [Although the wave equation $v = f\lambda$ relates wave speed, frequency, and wavelength, the wave speed is constant for a given medium. Wavelength and frequency are the only variables.[1]][Wave speed is dependent only on the medium in which the wave is propagating, so will not change when frequency changes.[2]]

I have explicitly addressed the wave equation.[1]

I have used the relevant theory: the dependence of wave speed on the medium.[2]

16 **a** $v = f\lambda = 10 \times 0.25 = 2.5$ m s^{-1} (1 MARK)

$\lambda = \frac{v}{f} = \frac{2.5}{15} = 0.17$ m (1 MARK)

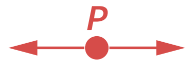
b $v = \frac{\lambda}{T} = \frac{0.25}{2.0} = 0.125$ m s^{-1} (1 MARK)

$\lambda = \frac{v}{f} = \frac{0.125}{2.0} = 0.063$ m (1 MARK)

17 $f = \frac{v}{\lambda} = \frac{70}{0.020} = 3.5 \times 10^3$ Hz

18 **a** $\lambda = vT = 0.40 \times 8.0 = 3.2$ m

b Point P moves back and forth in the direction of the wave, since the wave is longitudinal.



19 $T = 8.0$ s from graph

$\lambda = vT = 330 \times 8.0$ (1 MARK)

$\lambda = 2.6 \times 10^3$ m (1 MARK)

20 **a** $T = 20.0$ minutes $= 20.0 \times 60.0$ s $= 1.20 \times 10^3$ s

$f = \frac{1}{T} = \frac{1}{1.20 \times 10^3} = 8.33 \times 10^{-4}$ Hz

b $\lambda = 500$ km $= 5.00 \times 10^5$ m

$v = f\lambda = 8.33 \times 10^{-4} \times 5.00 \times 10^5 = 417$ m s^{-1}

21 $f = 30$ kHz $= 3.0 \times 10^4$ Hz

$\lambda = \frac{v}{f} = \frac{340}{3.0 \times 10^4} = 0.011$ m $= 11$ mm

22 Based on wave equation, longest wavelength occurs at the lowest frequency 85 Hz. (1 MARK)

$\lambda = \frac{v}{f} = \frac{340}{85} = 4.0$ m (1 MARK)

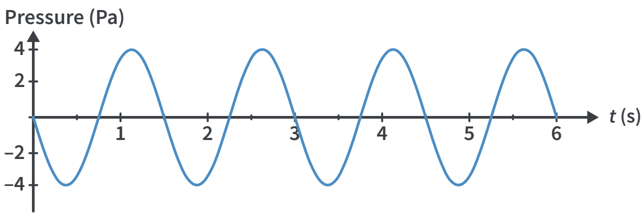
23 $\lambda = \frac{1}{4}$ length of tube $= \frac{1}{4} \times 2.00 = 0.500$ m

$v = f\lambda = 534 \times 0.500 = 267$ m s^{-1} (1 MARK)

The unknown gas is carbon dioxide. (1 MARK)

24 Use graph and wave speed provided to determine period is 1.5 s.

Initially, pressure at point Q decreases as wave is moving to the right.



I have drawn axes with correct labels and units.

I have included an appropriate and consistent scale on the axes.

I have drawn a sinusoidal graph starting from (0,0) and finishing at (6,0).

I have drawn a wave with an amplitude of 4 Pa.

I have drawn a wave with a period of 1.5 s.

I have drawn a wave that initially decreases.

25 a $\lambda = 4$ m from either graph

b For lowest possible frequency, the wave has moved through $\frac{1}{4}$ of a cycle in 0.25 s (1 MARK)

$\frac{1}{4}T = 0.25$ s

$T = 1$ s

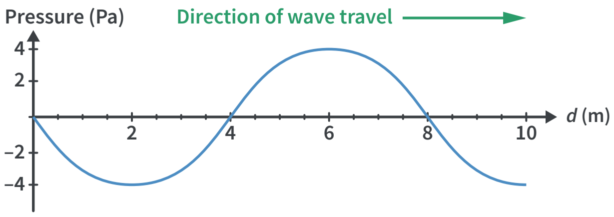
$f = \frac{1}{T} = 1$ Hz (1 MARK)

c $v = f\lambda = 1 \times 4 = 4$ m s^{-1}

26 a $\lambda = 8$ m from graph

b $T = \frac{\lambda}{T} = \frac{8}{2} = 4$ s

c 2 s is half a period, so the wave has moved half a wavelength to the right.



- I have drawn axes with the correct labels and units.
- I have included an appropriate and consistent scale on the axes.
- I have drawn a sinusoidal graph starting from (0,0) and finishing at (10,−4).
- I have drawn a wave with an amplitude of 4 Pa.
- I have drawn a wave with a wavelength of 8 m.
- I have drawn a wave that has shifted half a wavelength to the right.

Previous lessons

27 $\frac{L}{L_0} = \frac{1}{4}$

$\gamma = \frac{L_0}{L} = \frac{4}{1} = 4$ (1 MARK)

$4 = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

$v = 0.968c$ (1 MARK)

28 a $W = KE$

$qV = \frac{1}{2}mv^2$

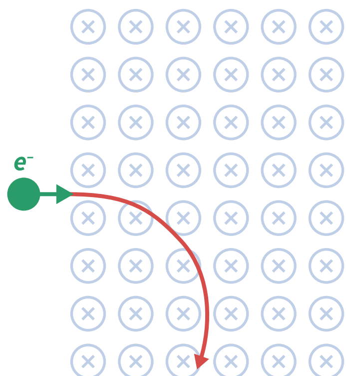
$1.6 \times 10^{-19} \times V = \frac{1}{2} \times 9.1 \times 10^{-31} \times (5.0 \times 10^7)^2$ (1 MARK)

$V = 7.1 \times 10^3$ V (1 MARK)

b $r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 5.0 \times 10^7}{1.6 \times 10^{-19} \times 350}$ (1 MARK)

$r = 8.1 \times 10^{-7}$ m (1 MARK)

c Remember, when using the right-hand rule to determine path direction, an electron has a negative charge.



- I have drawn a clockwise circular path.

Key science skills

29 *Measurement uncertainty* $= \pm\frac{1}{2} \times$ *smallest increment* $= \pm\frac{1}{2} \times 10 = \pm 5$ Hz

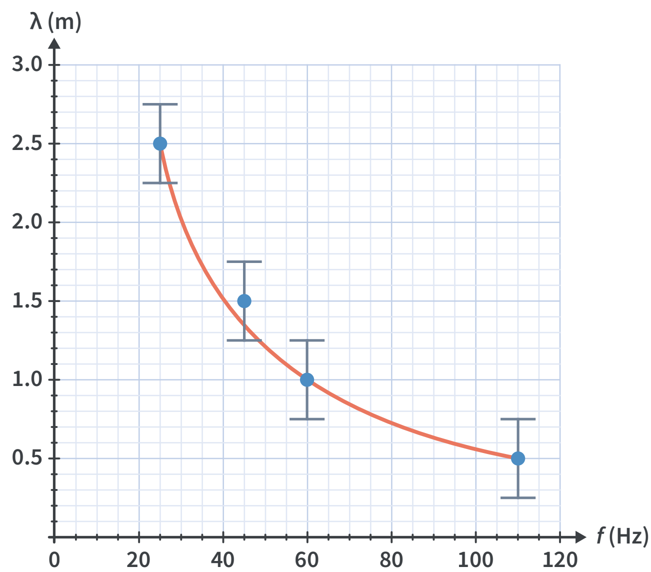
30 *gradient* $= \frac{rise}{run} = \frac{\lambda}{T} = v$ (1 MARK)

Use two points on a line of best fit which passes through all uncertainty bars to determine rise and run.

$v = \frac{3.5}{7.0} = 0.50$ m s^{-1} (1 MARK)

Depending on the line of best fit drawn, answers between 0.44 m s^{-1} and 0.56 m s^{-1} are acceptable.

31



- I have identified the independent and dependent variables.
- I have drawn the horizontal axis as the independent variable, and included correct units.
- I have drawn the vertical axis as the dependent variable, and included correct units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each point of data.

9B

- I have drawn correctly sized uncertainty bars.
- I have drawn a smooth curve of best fit which passes through all uncertainty bars.

9C The Doppler effect

Theory review questions

1 A **2** B **3** C **4** B

5 A **6** C

Exam-style questions

This lesson

7 Speed relative to student A: $V_S + V_A$ (1 MARK)

Speed relative to student B: $V_S - V_B$ (1 MARK)

8 $v_{relative} = 340 - 30.0 = 310 \text{ m s}^{-1}$

9 Only the source is moving, so there is no change in relative wave speed.

Umpire running towards: $v_{relative} = 340 \text{ m s}^{-1}$ (1 MARK)

Umpire running away: $v_{relative} = 340 \text{ m s}^{-1}$ (1 MARK)

10 [The sound waves have increased frequency due to the Doppler effect.[1]] [Because the police car moves towards the observer between the formation of each wave front, the wavelength decreases and so the frequency has increased.[2]]

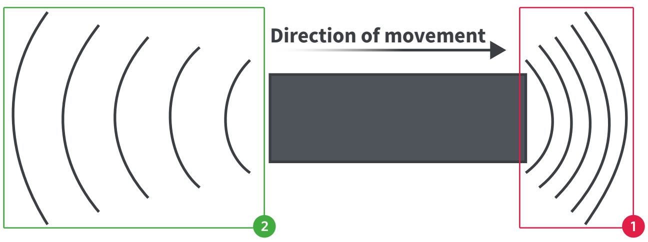
- I have explicitly addressed the physical principle involved.[1]
- I have used the relevant theory: motion in a medium.[2]
- I have related my answer to the context of the question.

11 The distance between fronts has increased.

12 [When the wave receiver travels away from the sound source, the frequency of sound measured will have decreased.[1]] [When the receiver moves away from the sound source, there is a longer period between each wave crest reaching it, meaning that it records a lower frequency.[2]] [This is the Doppler effect.[3]]

- I have explicitly addressed how frequency changes.[1]
- I have used the relevant theory: motion in a medium.[2]
- I have explicitly addressed the physical principle involved.[3]

13



- I have drawn the waves in front of the source with shorter wavelength.[1]
- I have drawn the waves behind the source with longer wavelength.[2]

14 **a** The frequency has increased.

b [The frequency will be the same as that recorded while stationary.[1]] [Despite both cars being in motion, they are stationary relative to each other.[2]]

- I have explicitly addressed the change in wave frequency.[1]
- I have used the relevant theory: motion in a medium.[2]

c [The frequency will be lower than that recorded while stationary.[1]] [This is because car *A* and car *B* are moving further apart.[2]]

- I have explicitly addressed the change in wave frequency.[1]
- I have used the relevant theory: motion in a medium.[2]

15 [Tamika is correct[1]] [as wave speed relative to the medium is dependent on the medium only.[2]] [A frequency change occurs due to the increase in wave speed relative to the detector. This causes more wave cycles to reach the detector per second, increasing frequency.[3]]

- I have explicitly addressed which student is correct.[1]
- I have used the relevant theory: wave speed is dependent on the medium only.[2]
- I have explicitly addressed why there is a frequency change.[3]
- I have used the relevant theory: motion in a medium.

Previous lessons

16 Speed of particle relative to comet is $0.70c$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.70c)^2}{c^2}}} = 1.40$$ (1 MARK)

$$L = \frac{L_0}{\gamma} = \frac{3000}{1.40}$$ (1 MARK)

$L = 2.1 \times 10^3 \text{ m}$ (1 MARK)

17 $KE = W$

$\frac{1}{2}mv^2 = qV$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = 1.6 \times 10^{-19} \times 40 \times 10^3$ (1 MARK)

$v = 1.19 \times 10^8 \text{ m s}^{-1}$

$v = 0.40c$ (1 MARK)

Key science skills

18 Independent variable: vehicle speed; Dependent variable: detected frequency; Controlled variable: source frequency **OR** wave medium

19 Qualitative: Bodhi; Quantitative: Tane

9D Wave interference and path difference

Theory review questions

1 C	**2** B	**3** A	**4** D
5 C	**6** C	**7** B	**8** A

Exam-style questions

This lesson

9 a From diagram $PM = 2\lambda$ and $QM = 3\lambda$

$p.d. = |PM - QM|$

$4.0 = |2\lambda - 3\lambda|$ (1 MARK)

$\lambda = 4.0$ cm (1 MARK)

b From diagram $PN = 2\lambda$ and $QN = 1.5\lambda$ (1 MARK)

$p.d. = |PN - QN| = |2 \times 4.0 - 1.5 \times 4.0| = 2.0$ cm (1 MARK)

10 [The sound is louder at position X because $p.d. = 0$ at this point which means constructive interference occurs whereas, at position Y, $p.d. = 0.5\lambda$ so destructive interference occurs.[1]][Interference is a wave behaviour.[2]]

- I have explicitly addressed the question.[1]
- I have explicitly addressed wave behaviour.[2]
- I have used the relevant theory: relationship between path difference and type of interference.
- I have related my answer to the context of the question.

11 $p.d. = \left(n - \frac{1}{2}\right)\lambda$

$|PT - 15.0| = \left(3 - \frac{1}{2}\right) \times 5.00$ (1 MARK)

$PT = 27.5$ cm (1 MARK)

12 a Y is the 2nd loud point from centre.

$p.d. = n\lambda = 2 \times 0.60 = 1.2$ m (1 MARK)

$p.d. = |S_1Y - S_2Y|$

$1.2 = |1.0 - S_2Y|$ (1 MARK)

$S_2Y = 2.2$ m (1 MARK)

b i $p.d. = 0$ so constructive interference (high intensity) occurs.

ii $\frac{p.d.}{\lambda} = \frac{1.2}{0.80} = 1.5$ (1 MARK)

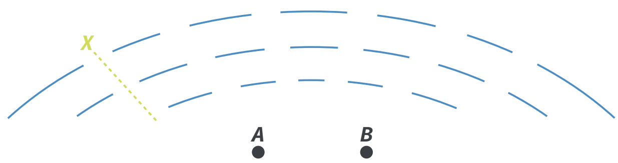
$p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 2$ so destructive interference (low intensity) occurs. (1 MARK)

13 a $p.d. = |7.0 - 12.0| = 5.0$ cm

$\frac{p.d.}{\lambda} = \frac{5.0}{2.0} = 2.5$ (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 3$ so destructive interference occurs at X. (1 MARK)

b



Any point along the green line (the third nodal line) is an acceptable location for X.

14 a [Loud regions are caused by constructive interference.[1]][Quiet regions are caused by destructive interference.[2]][These regions alternate as Mark walks towards speaker A because the type of interference depends on the path difference.[3]][Constructive interference occurs where $p.d. = n\lambda$ and destructive interference occurs where $p.d. = \left(n - \frac{1}{2}\right)\lambda$.[4]]

- I have explicitly addressed the cause of loud regions.[1]
- I have explicitly addressed the cause of quiet regions.[2]
- I have explicitly addressed the alternation between loud and quiet regions.[3]
- I have used the relevant theory: relationship between path difference and type of interference.[4]
- I have related my answer to the context of the question.

b $\lambda = \frac{v}{f} = \frac{340}{680} = 0.500$ m (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(3 - \frac{1}{2}\right) \times 0.500 = 1.25$ m (1 MARK)

Distance from centre is $\frac{p.d.}{2} = 0.625$ m (1 MARK)

15 a $v = f\lambda = 4.0 \times 0.015 = 0.060$ m s^{-1}

b $p.d. = n\lambda$

$|5.0 - 2.0| = 1.5n$ (1 MARK)

$n = 2$ $\therefore P$ is the 2nd antinode from the centre. (1 MARK)

16 a $p.d. = |4.50 - 7.00| = 2.50$ m

$p.d. = \left(n - \frac{1}{2}\right)\lambda$

$2.50 = \left(3 - \frac{1}{2}\right)\lambda$ (1 MARK)

$\lambda = 1.00$ m (1 MARK)

b $f = \frac{v}{\lambda} = \frac{340}{1.00} = 340$ Hz

17 Let the speed of sound be 340 m s^{-1} (note that speed does not affect the result).

For 1st experiment $\lambda = \frac{v}{f} = \frac{340}{400} = 0.850$ m

$p.d. = n\lambda = 1 \times 0.850 = 0.850$ m (1 MARK)

For 2nd experiment $p.d. = \left(n - \frac{1}{2}\right)\lambda$

$0.850 = \left(2 - \frac{1}{2}\right)\lambda$ (1 MARK)

$\lambda = 0.567$ m

$f = \frac{v}{\lambda} = \frac{340}{0.567} = 600$ Hz (1 MARK)

Previous lessons

18 a Length contraction.

b $\gamma = \frac{L_0}{L} = \frac{100}{20} = 5.0$ (1 MARK)

$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$5.0 = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$v = 0.9798c = 2.939 \times 10^8 \text{ m s}^{-1}$ (1 MARK)

Muon's frame measures proper time.

$t_0 = \frac{L}{v} = \frac{20}{2.939 \times 10^8} = 6.8 \times 10^{-8} \text{ s}$ (1 MARK)

19 $\Phi_2 = B_\perp A$

$\Phi_2 = (2.4 \times 10^{-2}) \times (4.0 \times 10^{-3}) = 9.6 \times 10^{-5} \text{ Wb}$ (1 MARK)

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$

$\varepsilon = 15 \times \frac{9.6 \times 10^{-5} - 0}{0.25 - 0}$ (1 MARK)

$\varepsilon = 5.8 \times 10^{-3} \text{ V}$ (1 MARK)

Key science skills

20 a Yes. The measurements taken and the formula used will allow Batman to determine the wavelength.

b Use a sound intensity meter to identify the node rather than listening for it.

c [Measure the path difference at multiple nodal points and repeat the calculation.[1]][This provides multiple valid measurements for wavelength which can be averaged to reduce the effect of random errors.[2]]

I have explicity addressed a way to improve accuracy.[1]

I have used the relevant theory: the relationship between random error and accuracy.[2]

9E Resonance

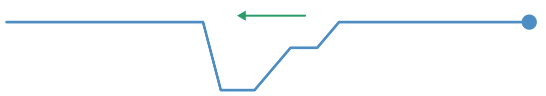
Theory review questions

1 D **2** B **3** A **4** C **5** A

Exam-style questions

This lesson

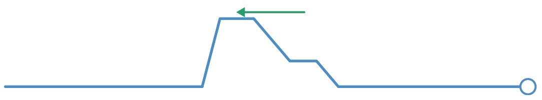
6 a



I have drawn the wave pulse reflected and inverted.

I have indicated the direction of travel.

b



I have drawn the wave pulse reflected but not inverted.

I have indicated the direction of travel.

7 When the amplitude of oscillation significantly increases.

8 [Objects resonate when they are being forced at their natural frequency. Each forced oscillation at the natural frequency adds energy to the system which builds the amplitude of oscillation.[1]][A glass can be broken by a human voice because the glass can resonate due to the voice, such that the amplitude of oscillation becomes sufficiently large to break the glass.[2]]

I have used the relevant theory: resonance.[1]

I have explicitly addressed how a voice can break glass.[2]

9 [Task 1 will cause the machine to vibrate most[1]][because its frequency (75 Hz) matches the natural frequency of the machine so it will resonate.[2]]

I have explicitly addressed which task will cause the machine to vibrate the most.[1]

I have used the relevant theory: resonance.[2]

10 [Francis is correct.[1]][Forcing oscillation of the swing at its natural frequency (resonance) will allow the energy from every push to efficiently build up, achieving a high swing.[2]][George is incorrect because, when the forcing frequency is not the natural frequency, the force of a push can act against the oscillation of the swing, decreasing swing height.[3]]

I have explicitly addressed who is correct.[1]

I have used the relevant theory: resonance.[2]

I have explicitly addressed why George is incorrect.[3]

Previous lessons

11 Clock is running at half the speed: $\gamma = 2$ (1 MARK)

$KE = (\gamma - 1)mc^2 = (2-1) \times 1.2 \times 10^5 \times (3 \times 10^8)^2$ (1 MARK)

$KE = 1.1 \times 10^{22} \text{ J}$ (1 MARK)

12 $KE_{initial} = (\gamma - 1)mc^2 = (4.5 - 1) \times mc^2$ (1 MARK)

$KE_{initial} = KE_{first\ particle\ final} + KE_{second\ particle\ final}$

$3.5 \times mc^2 = mc^2 + KE_{second\ particle\ final}$ (1 MARK)

$KE_{second\ particle\ final} = 2.5 \times mc^2$ (1 MARK)

13 [The magnetic flux through the coil is decreasing[1]][downwards.[2]][By Lenz's law, the induced current creates a magnetic field which opposes the change in flux[3]][so the magnetic field points downwards[4]][Using the right-hand coil rule, with thumb pointing down to represent the induced magnetic field,[5]][the current direction is clockwise.[6]]

I have explicitly addressed whether the magnetic flux is increasing or decreasing.[1]

I have explicitly addressed the direction of magnetic flux.[2]

I have used the relevant theory: Lenz's law.[3]

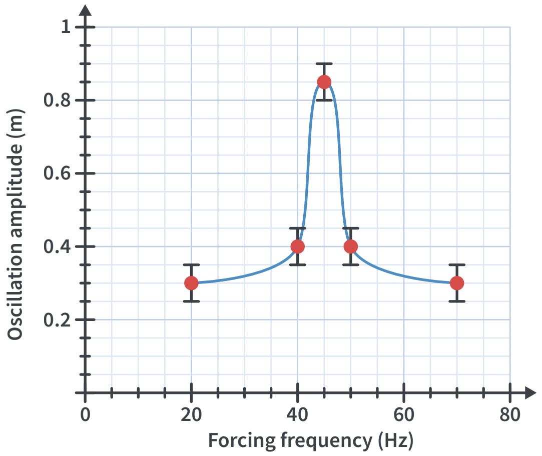
I have explicitly addressed the direction of the induced magnetic field.[4]

I have explicitly referenced the right-hand coil rule.[5]

I have explicitly addressed the direction of current.[6]

Key science skills

14 a



I have drawn the horizontal axis as the independent variable, and included correct labels and units.

I have drawn the vertical axis as the dependent variable, and included correct labels and units.

I have used an appropriate and consistent scale on the axes.

I have plotted each point of data.

I have drawn correctly sized uncertainty bars.

I have fitted an appropriate curve to the data which passes through all uncertainty bars.

b 45 Hz

9F Standing waves

Theory review questions

1 D **2** C **3** D **4** A

5 B **6** A **7** D

Exam-style questions

This lesson

8 **a** $\lambda = \frac{2L}{n} = \frac{2 \times 5.0}{1} = 10$ m

b $f = \frac{nv}{2L} = \frac{1 \times 200}{2 \times 5.0} = 20$ Hz **OR** $f = \frac{v}{\lambda} = \frac{200}{10} = 20$ Hz

c $\lambda = \frac{2L}{n} = \frac{2 \times 5.0}{2} = 5.0$ m (1 MARK)

$f = \frac{nv}{2L} = \frac{2 \times 200}{2 \times 5.0} = 40$ Hz (1 MARK)

OR

$\lambda = \frac{2L}{n} = \frac{2 \times 5.0}{2} = 5.0$ m (1 MARK)

$f = \frac{v}{\lambda} = \frac{200}{5.0} = 40$ Hz (1 MARK)

9 **a** $\lambda = \frac{2L}{n} = \frac{2 \times 0.690}{3} = 0.460$ m

b $f = \frac{nv}{2L} = \frac{3 \times 330}{2 \times 0.690} = 717$ Hz

OR

$f = \frac{v}{\lambda} = \frac{330}{0.460} = 717$ Hz

c $\lambda = \frac{2L}{n} = \frac{2 \times 0.690}{4} = 0.345$ m (1 MARK)

$f = \frac{nv}{2L} = \frac{4 \times 330}{2 \times 0.690} = 957$ Hz (1 MARK)

OR

$\lambda = \frac{2L}{n} = \frac{2 \times 0.690}{4} = 0.345$ m (1 MARK)

$f = \frac{v}{\lambda} = \frac{330}{0.345} = 957$ Hz (1 MARK)

10 **a** $\lambda = \frac{4L}{n} = \frac{4 \times 0.90}{1} = 3.6$ m

b $f = \frac{nv}{4L} = \frac{1 \times 360}{4 \times 0.90} = 1.0 \times 10^2$ Hz

OR

$f = \frac{v}{\lambda} = \frac{360}{3.6} = 1.0 \times 10^2$ Hz

c For one fixed end, second lowest frequency resonance is the third harmonic ($n = 3$).

$\lambda = \frac{4L}{3} = \frac{4 \times 0.90}{3} = 1.2$ m (1 MARK)

$f = \frac{nv}{4L} = \frac{3 \times 360}{4 \times 0.90} = 3.0 \times 10^2$ Hz (1 MARK)

OR

$\lambda = \frac{4L}{3} = \frac{4 \times 0.90}{3} = 1.2$ m (1 MARK)

$f = \frac{v}{\lambda} = \frac{360}{1.2} = 3.0 \times 10^2$ Hz (1 MARK)

11 **a** Effective length of string has halved: $L = \frac{0.325}{2} = 0.1625$ m (1 MARK)

$\lambda = \frac{2L}{n} = \frac{2 \times 0.1625}{1} = 0.325$ m (1 MARK)

b Frequency has doubled since effective length of string and wavelength has halved. (1 MARK)

$f = 2 \times 440 = 880$ Hz (1 MARK)

OR

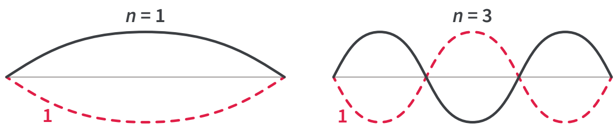
$v = f\lambda = 440 \times 0.650 = 286$ m s^{-1} (1 MARK)

$f = \frac{nv}{2L} = \frac{1 \times 286}{2 \times 0.1625} = 880$ Hz (1 MARK)

12 $\lambda = \frac{4L}{n}$ $\therefore 3.0 = \frac{4L}{1}$ (1 MARK)

$L = 0.75$ m (1 MARK)

13 a

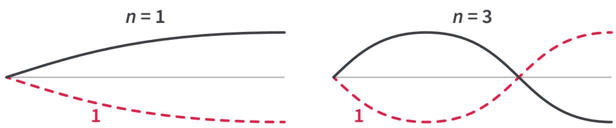


I have shown the envelope (i.e. the max. and min. positions) for each standing wave.[1]

I have drawn a standing wave with one half-wavelength for the 1st harmonic.

I have drawn a standing wave with three half-wavelengths for the 3rd harmonic.

b



I have shown the envelope (i.e. the max. and min. positions) for each standing wave.[1]

I have drawn a standing wave with one quarter-wavelength for the 1st harmonic.

I have drawn a standing wave with three quarter-wavelengths for the 3rd harmonic.

14 [A standing wave is formed on a string by the superposition of a travelling wave with its own reflection[1]][which travels in the opposite direction with the same amplitude and frequency.[2]][The superposition of these waves produces antinodes (constructive interference) and nodes (destructive interference).[3]]

I have explicitly addressed the formation of standing waves.[1]

I have used the relevant theory: the required qualities of the interfering waves.[2]

I have used the relevant theory: the interference pattern of a standing wave.[3]

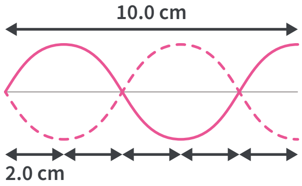
I have included a diagram showing the formation of a standing wave and its nodes and antinodes (similar to Figure 1 in lesson 9F).

15 [A travelling wave has points of maximum amplitude (i.e. crests and troughs for a transverse wave) that travel in the direction of wave propagation,[1]][whereas a standing wave has constant points of maximum variation of amplitude called antinodes.[2]]

I have explicitly addressed maximum amplitude in travelling waves.[1]

I have explicitly addressed maximum amplitude in standing waves.[2]

16 a [The string has one fixed end.[1]][The distance between a fixed end (node) and its nearest antinode must be one quarter of a wavelength. In this case we have $\frac{\lambda}{4} = 2.0$ cm so $\lambda = 8.0$ cm. We also know $L = 10.0$ cm and n = 5.[2]][This data meets the constraints of a string with one fixed end: $\lambda = \frac{4L}{n}$.[3]]



I have explicitly addressed the question.[1]

I have used the provided data in my answer.[2]

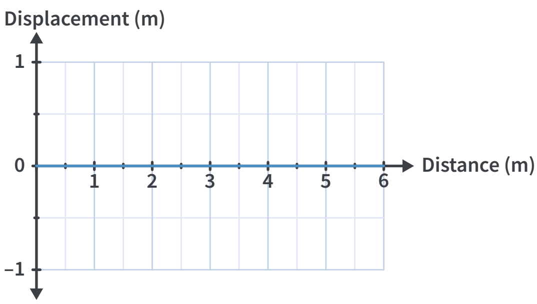
I have used the relevant theory: wavelength of standing waves with one fixed end.[3]

I have drawn a diagram of a fifth harmonic wave with one fixed end which shows the distance between nodes and antinodes.

b $f = \frac{nv}{4L} = \frac{5 \times 300}{4 \times 10.0 \times 10^{-2}}$ (1 MARK)

$f = 3.8 \times 10^3$ Hz (1 MARK)

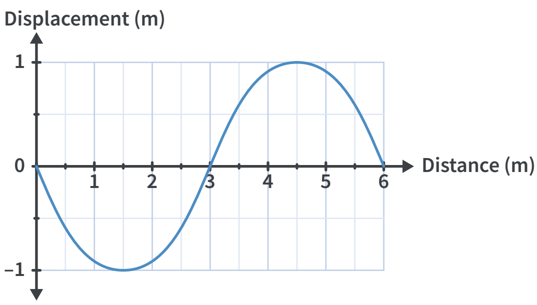
17 a 1.0 second later is one quarter of a period later.



I have drawn a flat line at 0 m displacement.

I have labelled the horizontal and vertical axes, including units and a scale.

b 2.0 seconds later is half a period later.



I have drawn a sinusoidal graph that passes through (0, 0), (1.5, −1), (3, 0), (4.5, 1), and (6, 0).

I have labelled the horizontal and vertical axes, including units and a scale.

c $v = \frac{\lambda}{T} = \frac{6}{4.0} = 1.5 \text{ m s}^{-1}$ (1 MARK)

$f = \frac{nv}{2L} = \frac{5 \times 1.5}{2 \times 6}$ (1 MARK)

$f = 0.63$ Hz (1 MARK)

18 Two nodes and two antinodes is only possible for the third harmonic of a string with one fixed end.

$f = \frac{nv}{4L} \therefore 10 = \frac{3 \times 20}{4L}$ (1 MARK)

$L = 1.5$ m (1 MARK)

Previous lessons

19 a [The current in the coil reverses direction every half turn (AC). Slip rings provide a constant connection so the output to the oscilloscope will also be AC.[1]][To generate a DC signal, a split ring commutator would be needed instead of slip rings.[2]]

- I have explicitly addressed why an AC signal is produced.[1]
- I have explicitly addressed what would be required to produce a DC signal.[2]
- I have used the relevant theory: slip rings and split ring commutators in generators.

b $T = 4 \times 30$ ms $= 0.12$ s (1 MARK)

$f = \frac{1}{0.12} = 8.3$ Hz (1 MARK)

c [If the rotational speed of the coil was tripled, the time period of each emf cycle would reduce by a factor of 3 (or the emf frequency would triple)[1]][and the amplitude of the emf would triple.[2]]

- I have explicitly addressed the impact on emf time period or frequency.[1]
- I have explicitly addressed the impact on emf amplitude.[2]

20 $KE = (\gamma - 1)mc^2 = (5 - 1) \times 15\,000 \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 5.4 \times 10^{21}$ J (1 MARK)

Key science skills

21 [Taking multiple readings and then calculating the average will reduce the effects of random error in the experiment.[1]][Having a friend repeat the experiment will help James determine the reproducibility of his results.[2]]

- I have explicitly addressed the effect of taking multiple readings.[1]
- I have explicitly addressed that effect of having a friend repeat the experiment.[2]

9G Diffraction

Theory review questions

1 C	**2** B	**3** A	**4** D
5 A	**6** B		

Exam-style questions

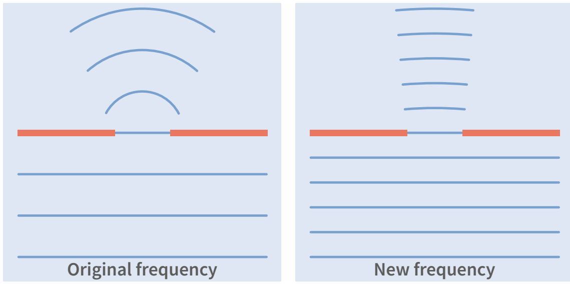
This lesson

7 D

8 [Speaker *B* can be heard with greater intensity[1]][because its sound will diffract more.[2]][For speaker *B*, $\frac{\lambda}{w} = \frac{3.0}{2.0} = 1.5$ which is greater than $\frac{\lambda}{w} = \frac{1.0}{2.0} = 0.50$ for speaker *A*.[3]]

- I have explicitly addressed which sound will be heard with greater intensity.[1]
- I have used the relevant theory: extent of diffraction.[2]
- I have used calculations to support my answer.[3]

9 a



- I have drawn a pattern for the new frequency with shorter wavelengths.
- I have drawn a pattern for the new frequency with less diffraction.

b [Increasing frequency decreases wavelength[1]][which reduces the ratio $\frac{\lambda}{w}$ so less diffraction occurs.[2]]

- I have used the relevant theory: relationship between frequency and wavelength.[1]
- I have used the relevant theory: extent of diffraction.[2]

10 [Hannah's suggestion will work but the others will not.[1]][To double *x* the students will need to double the extent of diffraction by doubling the ratio $\frac{\lambda}{w}$.[2]][Halving the frequency doubles the wavelength (and the ratio),[3]][halving the distance between the speaker and the barrier will not affect the ratio,[4]][and doubling the gap width will halve the ratio.[5]]

- I have explicitly addressed which suggestions are correct and incorrect.[1]
- I have used the relevant theory: extent of diffraction.[2]
- I have explicitly addressed Hannah's suggestion.[3]
- I have explicitly addressed Ash's suggestion.[4]
- I have explicitly addressed Shahan's suggestion.[5]

11 [The trombonist is sliding up the frequency range.[1]][Increasing frequency decreases wavelength[2]][and the ratio $\frac{\lambda}{w}$, reducing diffraction out the door.[3]]

- I have explicitly addressed which way the trombonist is sliding.[1]
- I have used the relevant theory: relationship between frequency and wavelength.[2]
- I have used the relevant theory: extent of diffraction.[3]

12 [Campbell's bark diffracts more[1]][as the ratio $\frac{\lambda}{w}$ is greater.[2]][For Campbell's bark, $\frac{\lambda}{w} = \frac{1.8}{0.60} = 3.0$. For Dion's bark, $\lambda = \frac{340}{850} = 0.400$ m so $\frac{\lambda}{w} = \frac{0.400}{0.20} = 2.0$.[3]]

- I have explicitly addressed which dog's bark will diffract more.[1]
- I have used the relevant theory: extent of diffraction.[2]
- I have used calculations to support my answer.[3]

Previous lessons

13 **a** $V_{RMS} = \frac{V_{peak}}{\sqrt{2}}$ $\therefore 140 = \frac{V_{peak}}{\sqrt{2}}$ $\therefore V_{peak} = 198$ V

b Step-down transformer has 4:1 ratio. $\frac{N_1}{N_2} = \frac{4}{1}$ $\therefore \frac{2000}{N_2} = \frac{4}{1}$

$N_2 = 500$ turns

c Step-up transformer: $\frac{N_1}{N_2} = \frac{I_{lines}}{I_{alternator}}$ $\therefore \frac{1}{4} = \frac{I_{lines}}{40.0}$ $\therefore I_{lines} = 10.0$ A (1 MARK)

$P_{loss} = I_{lines}{}^2 R = 10.0^2 \times (1.00 + 1.00) = 200$ W (1 MARK)

d Step-up transformer: $\frac{N_1}{N_2} = \frac{V_{alternator}}{V_{AB}}$ $\therefore \frac{1}{4} = \frac{140}{V_{AB}}$

$V_{AB} = 560$ V (1 MARK)

Transmission lines: $V_{PQ} = V_{AB} - I_{lines} R = 560 - 10.0 \times (1.00 + 1.00)$

$V_{PQ} = 540$ V (1 MARK)

Step-down transformer: $\frac{N_1}{N_2} = \frac{V_{PQ}}{V_{XY}}$ $\therefore \frac{4}{1} = \frac{540}{V_{XY}}$ $\therefore V_{XY} = 135$ V (1 MARK)

14 $E = mc^2$ $\therefore$ each second: $5.7 \times 10^{28} = m \times (3.0 \times 10^8)^2$ (1 MARK)

$m = 6.3 \times 10^{11}$ kg lost each second. (1 MARK)

Key science skills

15 **a** Independent variable: gap size (w); dependent variable: diffraction pattern width (y); controlled variable: wavelength **OR** frequency **OR** wave medium.

b The experiment and its results are reproducible.

Chapter 9 Review

Section A

1 A **2** D **3** B **4** D **5** C

Section B

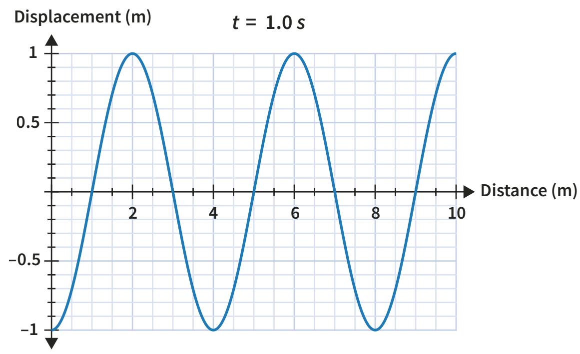
6 **a** From the displacement-distance graph $\lambda = 4$ m and from the displacement-time graph $T = 4$ s (1 MARK)

$v = \frac{\lambda}{T} = \frac{4}{4} = 1$ m s^{-1} (1 MARK)

b Particle C is moving upwards.

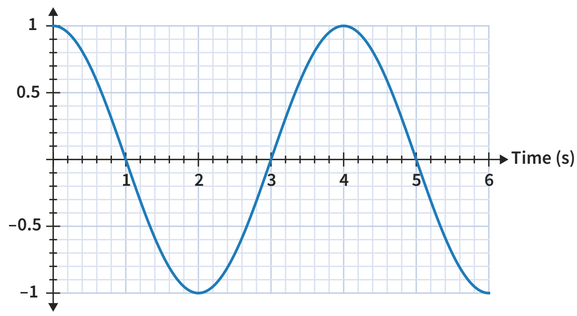
c Particle E is the only particle for which displacement decreases from 0 m just after $t = 0$ s

d



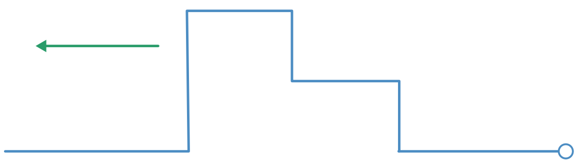
- I have labelled both axes including units.
- I have used an appropriate and consistent scale on both axes.
- I have drawn a sinusoidal wave with an amplitude of 1 m and a wavelength of 4 m.
- I have drawn a graph which starts with a minimum at $d = 0$ m and ends with a maximum at $d = 10$ m.

e



- I have labelled both axes including units.
- I have used an appropriate and consistent scale on both axes.
- I have drawn a sinusoidal wave with an amplitude of 1 m and a period of 4 s.
- I have drawn a graph which starts with a maximum at $t = 0$ s and ends with a minimum at $t = 6$ s.

7 **a**



- I have drawn a wave which has been reflected from the original wave.
- I have shown the wave travelling in the opposite direction.

b

I have drawn a wave which has been reflected from the original wave.

I have drawn a wave which has been inverted from the original wave.

I have shown the wave travelling in the opposite direction.

8 a [Mr Ridley is incorrect and Ms Hawes is correct.[1]] [The volume depends on the amplitude of the sound wave. The amplitude at a given point will be large if constructive interference is occurring and smaller if destructive interference is occurring.[2]] [This depends on the path difference to each speaker from that point.[3]]

I have explicitly addressed each opinion.[1]

I have used the relevant theory: wave interference.[2]

I have used the relevant theory: the relationship between path difference and interference.[3]

b $\lambda = \frac{v}{f} = \frac{340}{100} = 3.4$ m

For Toby: $p.d. = |S_1T - S_2T| = 8.4 - 5.0 = 3.4 \text{ m} = n\lambda$ where $n = 1$ $\therefore$ antinode. (1 MARK)

For Reginald: $p.d. = |S_1R - S_2R| = 2.7 - 1.0 = 1.7 \text{ m} = \left(n - \frac{1}{2}\right)\lambda$ where $n = 1$ $\therefore$ node. (1 MARK)

Toby will hear the sound well since he is at an antinode (constructive interference) whereas Reginald will not hear the sound well/at all since he is at a node (destructive interference). (1 MARK)

9 a Longest wavelength when $n = 1$ $\therefore \lambda = \frac{2L}{n} = \frac{2 \times 5.0}{1} = 10$ m

b $f = \frac{nv}{2L} = \frac{3 \times 28}{2 \times 5.0}$ (1 MARK)

$f = 8.4$ Hz (1 MARK)

c For one fixed end, third lowest frequency is when

$n = 5$ $\therefore f = \frac{nv}{4L} = \frac{5 \times 28}{4 \times 5.0}$ (1 MARK)

$f = 7.0$ Hz (1 MARK)

10 [Standing waves on strings with two fixed ends have nodes at both ends whereas standing waves on strings with one fixed end have a node at the fixed end and an antinode at the free end[1]] [which is a result of the constructive interference that occurs between a travelling wave and its reflection at the free end.[2]]

I have explicitly addressed the difference between two fixed ends and one fixed end.[1]

I have used the relevant theory: wave interference.[2]

11 a Destructive interference is creating a node at the position of the receiver.

b [The diffraction pattern will spread out more.[1]] [This is because diffraction is proportional to the ratio of $\frac{\lambda}{w}$ and a lower frequency means a longer wavelength.[2]]

I have explicitly addressed the question.[1]

I have used the relevant theory: extent of diffraction.[2]

c [The detected frequency will decrease as the receiver moves away.[1]] [This is the Doppler effect.[2]]

I have explicitly addressed the question.[1]

I have explicitly addressed the relevant physics principle.[2]

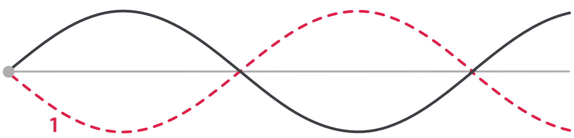
12 a $v = \frac{\lambda}{T} = \frac{9.00}{1.50} = 6.00 \text{ m s}^{-1}$

b $p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(2 - \frac{1}{2}\right) \times 9.00 = 13.5$ m (1 MARK)

$p.d. = |PA - PB|$ $\therefore 13.5 = |12.0 - PB|$ (1 MARK)

$PB = 25.5$ m (1 MARK)

13 a



I have shown the envelope (i.e. the max. and min. positions) for the standing wave.[1]

I have drawn a standing wave with five ‘quarter wavelengths’.

b $f = \frac{nv}{4L}$ $\therefore 30 = \frac{5 \times 6.0}{4L}$ (1 MARK)

$L = 0.25$ m (1 MARK)

14 $\lambda = \frac{2L}{4} = \frac{2 \times 1.40}{4} = 0.700$ m (1 MARK)

$v = \lambda f = 0.700 \times 250 = 175 \text{ m s}^{-1}$ (1 MARK)

15 a [A standing wave will not form[1]] [since the wavelength does not meet the constraints of a string with one fixed end (i.e. it does not fit $\lambda = \frac{4L}{n}$ where n is odd).[2]]

I have explicitly addressed the question.[1]

I have used the relevant theory: harmonics for one fixed end.[2]

b $p.d. = |SX_{reflected} - SX| = |12 - 4.0| = 8.0$ m (1 MARK)

$\frac{p.d.}{\lambda} = \frac{8.0}{2.0} = 4$ $\therefore p.d. = n\lambda$ where $n = 4$ (1 MARK)

Constructive interference is occurring at point X. (1 MARK)

16 a Diffraction

b [The observer is least likely to hear the trumpet[1]] [since it has the highest frequency (shortest wavelength) and diffraction is less significant for shorter wavelengths.[2]]

I have explicitly addressed which instrument the observer is least likely to hear.[1]

I have used the relevant theory: extent of diffraction.[2]

REVIEW

10A Electromagnetic waves

Theory review questions

1 B **2** C **3** D **4** D **5** A

Exam-style questions

This lesson

6 Radio, microwaves, infrared, orange light, ultraviolet, x-rays

7 Gamma, ultraviolet, blue light, red light, infrared, radio

8 D. Green has the second longest wavelength of the visible colours that mercury emits.

9 [An electromagnetic wave is produced by the acceleration of a charged particle.[1]][This produces a changing electric field and an associated changing magnetic field.[2]]

- I have explicitly addressed charged particles.[1]
- I have used the relevant theory: production of an electromagnetic wave.[2]

10 a $\Delta t = \frac{\Delta s}{v} = \frac{384\,400 \times 10^3}{3.0 \times 10^8} = 1.3$ s

b $\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{144 \times 10^6}$ (1 MARK)

$\lambda = 2.1$ m (1 MARK)

Previous lessons

11 a $E = mc^2$ ∴ each second $3.85 \times 10^{26} = m \times (3.0 \times 10^8)^2$ (1 MARK)

$m = 4.3 \times 10^9$ kg lost each second. (1 MARK)

b $E = mc^2 = 0.0276 \times 1.66 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$E = 4.1 \times 10^{-12}$ J (1 MARK)

c $\textit{Reactions per second} = \frac{\textit{Energy per second}}{\textit{Energy per reaction}} = \frac{3.85 \times 10^{26}}{4.1 \times 10^{-12}}$

$= 9.3 \times 10^{37}$ reactions per second

12 AC supply: $P = \frac{V_{RMS}^2}{R} = \frac{\left(\frac{325}{\sqrt{2}}\right)^2}{8.0} = 6.6 \times 10^3$ W (1 MARK)

DC supply: $P = \frac{V^2}{R} = \frac{250^2}{9.0} = 6.9 \times 10^3$ W

The DC supply provides more power. (1 MARK)

Key science skills

13 $\textit{Average} = \frac{532.3 + 532.5 + 532.1 + 531.9 + 532.7}{5} = 532.3$ nm (1 MARK)

$\textit{Uncertainty} = \frac{532.7 - 531.9}{2} = 0.4$ nm (1 MARK)

10B Refraction and reflection

Theory review questions

1 D **2** C **3** D **4** B

5 C **6** A

Exam-style questions

This lesson

7 $n = \frac{c}{v}$ ∴ $1.60 = \frac{3.0 \times 10^8}{v}$

$v = 1.9 \times 10^8$ m s^{-1}

8 $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ ∴ $1.00 \times \sin(45.0°) = n_2 \times \sin(30.0°)$ (1 MARK)

$n_2 = 1.41$ (1 MARK)

9 $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ ∴ $1.32 \times \sin(42°) = 1.40 \times \sin(\theta_2)$ (1 MARK)

$\theta_2 = \sin^{-1}\left(\frac{1.32 \times \sin(42°)}{1.40}\right) = 39°$ (1 MARK)

10 540 nm $= 5.40 \times 10^{-7}$ m

$v = f\lambda = 4.085 \times 10^{14} \times 5.40 \times 10^{-7} = 2.21 \times 10^8$ m s^{-1} (1 MARK)

$n = \frac{c}{v}$ ∴ $n = \frac{3.0 \times 10^8}{2.21 \times 10^8}$ (1 MARK)

$n = 1.4$ (1 MARK)

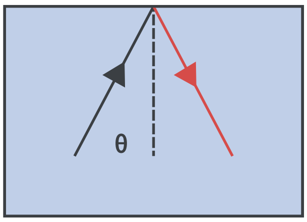
11 $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.28}{1.46}\right)$ (1 MARK)

$\theta_c = 61.2°$ (1 MARK)

12 $n_1\sin(\theta_c) = n_2$ ∴ $1.7 \times \sin(48°) = n_2$ (1 MARK)

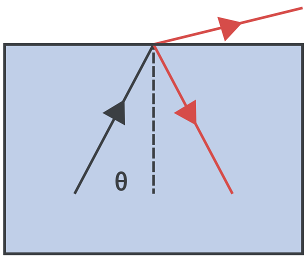
$n_2 = 1.3$ (1 MARK)

13 a



- I have drawn the reflected ray with angle of reflection equal to angle of incidence.

b



- I have drawn the reflected ray with angle of reflection equal to angle of incidence.
- I have drawn the refracted ray with angle of refraction greater than angle of incidence.

14 $v_2 = 1.2 \times v_1$

$n_1v_1 = n_2v_2$ ∴ $\frac{v_2}{v_1} = \frac{n_1}{n_2} = 1.2$ (1 MARK)

$n_1\sin(\theta_1) = n_2\sin(\theta_2)$

$\theta_1 = \sin^{-1}\left(\frac{n_2}{n_1} \times \sin(\theta_2)\right) = \sin^{-1}\left(\frac{1}{1.2} \times \sin(60°)\right)$ (1 MARK)

$\theta_1 = 46°$ (1 MARK)

15 [When the laser light passes into the stream of water, it can be guided by total internal reflection since water has a higher refractive index than air.[1]][Each subsequent reflection inside the stream will experience total internal reflection if it is incident at greater than the critical angle.[2]]

- I have explicitly addressed how the light is guided by the stream.[1]
- I have used the relevant theory: total internal reflection and critical angle.[2]

16 In air: $n_1\sin(\theta_c) = n_2 \ \therefore n_{fibre} \times \sin(50°) = 1.00$

$n_{fibre} = 1.3$ (1 MARK)

$n_{fibre} < n_{water}$ ∴ Total internal reflection will not occur in water. (1 MARK)

17 Despite moving through 3 media, we can treat this as a boundary between the first (air) and third (liquid) media because the boundaries are parallel.

$n_1\sin(\theta_1) = n_3\sin(\theta_3) \ \therefore 1.00 \times \sin(30°) = 1.33 \times \sin(\theta_3)$ (1 MARK)

$\theta_3 = 22°$ (1 MARK)

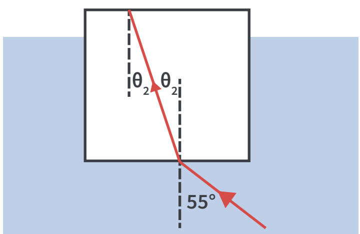
$\theta_1 - \theta_3 = 30 - 22 = 8°$ (1 MARK)

18 $v_{prism} = 0.80 \times v_{water}$ and $n_1v_1 = n_2v_2 \ \therefore \frac{v_{prism}}{v_{water}} = \frac{n_{water}}{n_{prism}} = 0.80$

$n_1\sin(\theta_1) = n_2\sin(\theta_2) \ \therefore \theta_2 = \sin^{-1}\left(\frac{n_{water}}{n_{prism}} \times \sin(\theta_1)\right)$

$\theta_2 = \sin^{-1}(0.80 \times \sin(55°))$ (1 MARK)

$\theta_2 = 41°$ (1 MARK)



Since the boundaries are parallel, the angle of incidence at the air-prism boundary is also 41°.

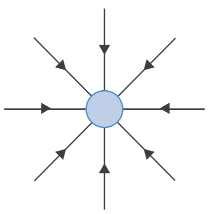
$v_{prism} = 0.80 \times v_{air}$ and $n_1v_1 = n_2v_2 \ \therefore \frac{v_{prism}}{v_{air}} = \frac{n_{air}}{n_{prism}} = 0.60$

$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{n_{air}}{n_{prism}}\right) = \sin^{-1}(0.60) = 37°$ (1 MARK)

$\theta_2 > \theta_c$ ∴ the ray will totally internally reflect (1 MARK)

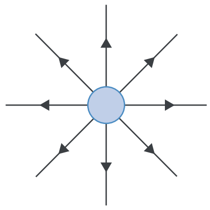
Previous lessons

19 a



- I have drawn the specified number of field lines.
- I have drawn evenly spaced field lines.
- I have drawn the gravitational field lines pointing towards the mass.

b



- I have drawn the specified number of field lines.
- I have drawn evenly spaced field lines.
- I have drawn the electric field lines pointing away from the positive charge.

20 a $P_{loss} = I^2R = 8.00^2 \times 9.00 = 576$ W

b $200 \times 10^3 \ V_{peak} = \frac{1}{\sqrt{2}} \times 200 \times 10^3 \ V_{RMS} = 1.41 \times 10^5 \ V_{RMS}$ (1 MARK)

$\frac{N_{out}}{N_{in}} = \frac{V_{out}}{V_{in}} = \frac{1.414 \times 10^5}{240} = 589 \ \therefore N_{out} : N_{in} = 589 : 1$ (1 MARK)

c Current increases by a factor of 4 ($I_2 = 4I_1$) (1 MARK)

Power loss increases by a factor of 16 since $P_{loss} = I^2R$ (1 MARK)

Key science skills

21 a Controlled: laser wavelength **OR** incident refractive index **OR** diamond refractive index; independent: angle of incidence; dependent: angle of refraction

b Use two points on a line of best fit to determine the gradient.

$gradient = \frac{rise}{run} = \frac{0.39 - 0.15}{0.90 - 0.35}$ (1 MARK)

$gradient = 0.44$ (1 MARK)

Depending on the line of best fit drawn, answers between 0.38 and 0.50 are acceptable.

c Using Snell's law: $n_1\sin(\theta_1) = n_2\sin(\theta_2) \ \therefore \frac{n_1}{n_2} = \frac{\sin(\theta_2)}{\sin(\theta_1)}$

In this case, $\sin(\theta_2) = \sin(\theta_r)$, $\sin(\theta_1) = \sin(\theta_i)$, $n_1 = 1.00$, and $n_2 = n_{diamond}$

$n_{diamond} = \frac{\sin(\theta_i)}{\sin(\theta_r)} = \frac{run}{rise} = \frac{1}{gradient}$

$n_{diamond} = \frac{1}{0.44} = 2.3$ (1 MARK)

$2.3 < 2.80$ ∴ The diamond is not real. (1 MARK)

10C Polarisation and colour dispersion

Theory review questions

1 B **2** A **3** D **4** D

Exam-style questions

This lesson

5 [The intensity would decrease,[1]][because the polarising filter will block the light which is not oscillating in the filter's polarisation direction.[2]]

- I have explicitly addressed the effect on light intensity.[1]
- I have used the relevant theory: polarisation.[2]

6 **a** Polarising filter 1 has a vertical transmission axis. (1 MARK)

Polarising filter 2 has a vertical transmission axis. (1 MARK)

b Polarising filter 1 has a vertical transmission axis. (1 MARK)

Polarising filter 2 has a horizontal transmission axis. (1 MARK)

7 Polarisation is solely a property of transverse waves so light must behave as a transverse wave.

8 [Diamonds exhibit a colourful shine because white light shone onto the diamond is dispersed into its constituent colours.[1]][White light consists of a continuous spectrum of the colours within the visible spectrum of light,[2]][and these colours are dispersed by the diamond because the diamond's refractive index is dependent on the wavelength (colour) of light.[3]]

- I have explicitly addressed why diamonds have a colourful shine.[1]
- I have used the relevant theory: white light.[2]
- I have used the relevant theory: colour dispersion.[3]

9 [Because the shorter wavelength colour (violet) is refracted more towards the normal than the longer wavelength colour (red),[1]][it can be concluded that the refractive index of the lens decreases as wavelength increases.[2]]

- I have used the relevant theory: refraction.[1]
- I have explicitly addressed the relationship between refractive index and wavelength.[2]

10 [Reflections off the surface of water are polarised,[1]][so wearing perpendicularly polarised sunglasses blocks the reflection reaching the wearer's eyes.[2]][Without these reflections, the observer can more clearly see light (and thus the object) coming from the bottom of the lake.[3]]

- I have used the relevant theory: polarisation from reflection.[1]
- I have used the relevant theory: polarisation filters.[2]
- I have explicitly addressed the question.[3]

Previous lesson

11 [No,[1]][because the gravitational field lines of a mass always point towards the mass.[2]]

- I have explicitly addressed whether the field lines represent a gravitational field.[1]
- I have used the relevant theory: gravitational field lines.[2]

12 From the graph:

Amplitude = 0.2 m (1 MARK)

Wavelength = 6 m (1 MARK)

13 $T = \frac{1}{f} = \frac{1}{10} = 0.10$ s

Key science skills

14 [No, the experiment is not valid[1]][because there is more than one independent variable in this experiment.[2]][For this experiment to be valid, the lens shape should be the only independent variable but the lens material has been changed too.[3]]

- I have explicitly addressed the validity of the experiment.[1]
- I have used the relevant theory: experimental validity and independent variables.[2]
- I have related my answer to the context of the question.[3]

15 [Random error can be reduced by repetition.[1]][Systematic error can be reduced by performing the experiment in a room with no ambient light.[2]]

- I have explicitly addressed how to reduce random error.[1]
- I have explicitly addressed how to reduce systematic error.[2]

10D Young's double slit experiment

Theory review questions

1 C **2** D **3** B **4** A **5** B

Exam-style questions

This lesson

6 A. Use $\Delta x = \frac{\lambda L}{d}$. When d increases Δx decreases.

7 A. Increasing frequency decreases wavelength.

Use $\Delta x = \frac{\lambda L}{d}$. When λ decreases Δx decreases.

8 **a** $p.d. = \left(n - \frac{1}{2}\right)\lambda \;\therefore 2.40 \times 10^{-6} = \left(4 - \frac{1}{2}\right) \times \lambda$ (1 MARK)

$\lambda = 6.86 \times 10^{-7}$ m (1 MARK)

b $p.d._{\text{4th dark}} = \left(n - \frac{1}{2}\right)\lambda \;\therefore 3.00 \times 10^{-6} = \left(4 - \frac{1}{2}\right) \times \lambda$ (1 MARK)

$\lambda = 8.57 \times 10^{-7}$ m (1 MARK)

$p.d._{\text{1st bright}} = n\lambda \;\therefore p.d._{\text{1st bright}} = 1 \times 8.57 \times 10^{-7} = 8.57 \times 10^{-7}$ m (1 MARK)

9 [Bright regions are caused by constructive interference[1]][and dark regions are caused by destructive interference.[2]]

- I have explicitly addressed the bright bands.[1]
- I have explicitly addressed the dark bands.[2]
- I have used the relevant theory: constructive and destructive interference.

10 a $\Delta x = \frac{\lambda L}{d}$ $\therefore 2.88 \times 10^{-5} = \frac{\lambda \times 1.50}{3.00 \times 10^{-2}}$

$\lambda = 576$ nm

b $\Delta x = \frac{\lambda L}{d}$ $\therefore 2.88 \times 10^{-5} = \frac{425 \times 10^{-9} \times L}{1.96 \times 10^{-2}}$

$L = 1.33$ m

c $\Delta x = \frac{\lambda L}{d}$ $\therefore 2.88 \times 10^{-5} = \frac{650 \times 10^{-9} \times 2.00}{d}$

$d = 4.51 \times 10^{-2}$ m

11 [Eva is correct.[1]][The path difference is zero in the centre,[2]][which means constructive interference occurs, and hence a bright band.[3]]

- I have explicitly addressed which student is correct.[1]
- I have used the relevant theory: path difference.[2]
- I have used the relevant theory: constructive interference.[3]

12 $p.d. = \left(n - \frac{1}{2}\right)\lambda$ $\therefore 9.15 \times 10^{-7} = 1.5 \times \lambda$ (1 MARK)

$\lambda = 6.10 \times 10^{-7}$ m (1 MARK)

$f = \frac{c}{\lambda} = \frac{3.0 \times 10^{8}}{6.10 \times 10^{-7}} = 4.9 \times 10^{14}$ Hz (1 MARK)

13 [The experiment supports a wave model of light[1]][because it produces an interference pattern which is a behaviour of waves.[2]][This provides evidence against a particle model of light which predicts two bright spots on a screen rather than an interference pattern.[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: how the double slit experiment supports the wave model.[2]
- I have used the relevant theory: why the particle model cannot explain the double slit result.[3]

14 a $\frac{p.d.}{\lambda} = \frac{1.50 \times 10^{-7}}{3.00 \times 10^{-9}} = 0.5$ (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 1$ so the point is the first dark band from the centre. (1 MARK)

X should be written above the first dark band to the left of the centre. (1 MARK)

b Consider point A for both experiments.

1st experiment:

$p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(2 - \frac{1}{2}\right) \times 300 \times 10^{-9} = 450 \times 10^{-9}$ m (1 MARK)

2nd experiment: $p.d. = n\lambda$ $\therefore 450 \times 10^{-9} = 1 \times \lambda$

$\lambda = 450 \times 10^{-9}$ m (1 MARK)

15 a Destructive interference.

b $\lambda = \frac{c}{f} = \frac{3.0 \times 10^{8}}{1.00 \times 10^{6}} = 3.0 \times 10^{2}$ m (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda$ $\therefore |d - 1.20 \times 10^{3}| = \left(1 - \frac{1}{2}\right) \times 3.0 \times 10^{2}$ (1 MARK)

$d = 1.35 \times 10^{3}$ m (1 MARK)

Previous lessons

16 $F_g = \frac{GMm}{r^2}$ $\therefore F_g = \frac{6.67 \times 10^{-11} \times 1.48 \times 10^{23} \times 20}{(400 \times 10^{3} + 2630 \times 10^{3})^2}$ (1 MARK)

$F_g = 22$ N (1 MARK)

17 a From the graph: $\lambda = 4 \times 10^{-6}$ m.

$v = f\lambda$ $\therefore v = 5.10 \times 10^{13} \times 4 \times 10^{-6}$ (1 MARK)

$v = 2.04 \times 10^{8}$ m s^{-1} (1 MARK)

b $n_1 v_1 = n_2 v_2$ $\therefore 1 \times 3.0 \times 10^{8} = n_2 \times 2.04 \times 10^{8}$ (1 MARK)

$n_2 = 1.5$ (1 MARK)

Key science skills

18 a The range of results is smallest for the 500 nm experiment.

b [Significant differences in the ratio of $\frac{\lambda}{\Delta x}$ suggest errors are having a significant effect.[1]][Given that L and d are constant between each experiment, the ratio $\frac{\lambda}{\Delta x}$ should also be constant since $\Delta x = \frac{\lambda L}{d}$.[2]]

[For the first experiment $\frac{\lambda}{\Delta x} \approx 2 \times 10^{-2}$. For the second experiment $\frac{\lambda}{\Delta x} \approx 6 \times 10^{-3}$. For the third experiment $\frac{\lambda}{\Delta x} \approx 9 \times 10^{-3}$.[3]]

- I have explicitly addressed the question.[1]
- I have used the relevant theory: fringe spacing equation.[2]
- I have used data to support my answer.[3]

Chapter 10 Review

Section A

1 C

2 C. Both boundaries show the prism has a higher refractive index than the other medium. At the top boundary, the light refracts more than at the bottom boundary, so the medium above the prism must have a smaller refractive index than the medium below the prism.

3 A   4 D   5 C

Section B

6 One year $= 60 \times 60 \times 24 \times 365 = 3.15 \times 10^{7}$ s (1 MARK)

$\Delta s = c\Delta t$ $\therefore \Delta s = 3.0 \times 10^{8} \times 3.15 \times 10^{7} \times 0.75 = 7.1 \times 10^{15}$ m (1 MARK)

7 [As an electron is accelerated,[1]][it causes a changing electric field which creates an associated changing magnetic field.[2]][This changing electromagnetic field is observed as an electromagnetic wave that is called light.[3]]

I have explicitly addressed the acceleration of an electron.[1]

I have used the relevant theory: production of electromagnetic waves.[2]

I have used the relevant theory: light as an electromagnetic wave.[3]

8 $n_A < n_B$ as, from B to A, the ray bends away from the normal.

9 $n_1 v_1 = n_2 v_2 \therefore 1.30 \times v_1 = 1.40 \times v_2$ (1 MARK)

$\frac{v_2}{v_1} = \frac{1.30}{1.40} = 0.929$ (1 MARK)

10 $n = \frac{c}{v} \therefore 1.80 = \frac{3.0 \times 10^8}{v}$

$v = 1.67 \times 10^8 \text{ m s}^{-1}$ (1 MARK)

$880 \text{ nm} = 8.80 \times 10^{-7} \text{ m}$

$v = f\lambda \therefore 1.67 \times 10^8 = f \times 8.80 \times 10^{-7}$ (1 MARK)

$f = 1.9 \times 10^{14} \text{ Hz}$ (1 MARK)

11 $p.d. = n\lambda \therefore 1.50 \times 10^{-6} = 3 \times \lambda$ (1 MARK)

$\lambda = 5.00 \times 10^{-7} \text{ m} = 500 \text{ nm}$ (1 MARK)

12 [The observer cannot see the light because the ray is being totally internally reflected which means no light is escaping.[1]][This occurs when the incident angle of the ray is larger than the critical angle.[2]]

I have explicitly addressed why the observer cannot see the ray.[1]

I have used the relevant theory: total internal reflection and critical angle.[2]

13 [Michael is incorrect.[1]][Although the speed of light is the same in all reference frames,[2]][light can travel slower than $3.0 \times 10^8 \text{ m s}^{-1}$ in different media.[3]]

I have explicitly evaluated Michael's statement.[1]

I have used the relevant theory: Einstein's second postulate.[2]

I have used the relevant theory: speed of light in different media.[3]

14 a $n_{\text{internal}} > n_{\text{external}}$ (1 MARK)

Angle of incidence must be greater than the critical angle. (1 MARK)

b Determine the refractive index which would have a critical angle of $\theta_c = 41.30°$.

$n_1 \sin(\theta_c) = n_2 \sin(90°) \therefore n_1 \sin(41.30°) = 1.000$ (1 MARK)

$n_1 = 1.515$ (1 MARK)

Therefore, total internal reflection (TIR) will occur for refractive indices greater than 1.515. TIR occurs for blue and violet but will not occur for red, yellow, and green. (1 MARK)

c Red (since it has the lowest refractive index so it travels fastest).

15 a [Violet, blue, green, yellow, orange, red.[1]][Shorter wavelengths refract more which places them towards the left.[2]]

I have explicitly addressed the colour order of light.[1]

I have used the relevant theory: refraction.[2]

b [Dispersion is occuring.[1]][Dispersion is the process of white light being separated into its constituent colours as each colour refracts by a different amount as it enters and leaves a medium.[2]]

I have explicitly addressed the relevant phenomenon.[1]

I have used the relevant theory: dispersion of white light.[2]

16 a No light would make it through the filter.

b [It suggests light behaves as a transverse wave[1]][because only transverse waves can be polarised.[2]]

I have explicitly addressed what polarisation suggests about the nature of light.[1]

I have used the relevant theory: polarisation.[2]

17 a $n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \;\therefore 1.00 \times \sin(43.2°) = 1.9 \sin(\theta_2)$ (1 MARK)

$\theta_2 = 21°$ (1 MARK)

b $\frac{p.d.}{\lambda} = \frac{1.60 \times 10^{-6}}{640 \times 10^{-9}} = 2.5$ (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 3$ so this point is the third dark band from the centre. (1 MARK)

The lock will not open. (1 MARK)

OR

$p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(2 - \frac{1}{2}\right) \times 640 \times 10^{-9}$ (1 MARK)

$p.d. = 960 \times 10^{-9} \text{ m}$ (1 MARK)

The path difference at the second dark band is not 1.60×10^{-6} m so the lock will not open. (1 MARK)

18 a $p.d. = n\lambda = 2 \times 480 \times 10^{-9}$ (1 MARK)

$p.d. = 9.60 \times 10^{-7} \text{ m}$ (1 MARK)

b $\Delta x = \frac{\lambda L}{d} = \frac{480 \times 10^{-9} \times 1.50}{3.00 \times 10^{-2}}$ (1 MARK)

$\Delta x = 2.40 \times 10^{-5} \text{ m}$ (1 MARK)

c The interference pattern would be closer together as the fringe spacing would be reduced.

d [A would remain an antinode.[1]][A is equidistant to both sources and therefore the path difference is always zero.[2]][This means that constructive interference occurs.[3]]

I have explicitly addressed the nature of A.[1]

I have used the relevant theory: path difference.[2]

I have used the relevant theory: how path difference affects wave interference.[3]

19 [Young's double slit experiment demonstrated an interference pattern[1]] [which is a wave property.[2]] [Therefore it supports a wave model of light.[3]] [A particle model incorrectly predicts two bright spots on a screen rather than the interference pattern.[4]]

- I have used the relevant theory: interference in the double slit experiment.[1]
- I have used the relevant theory: wave properties (interference).[2]
- I have explicitly addressed how the experiment supports a wave model.[3]
- I have explicitly addressed how the experiment provides evidence against a particle model.[4]

Unit 4, AOS 1 Review

Section A

1 D **2** B **3** C **4** C **5** D

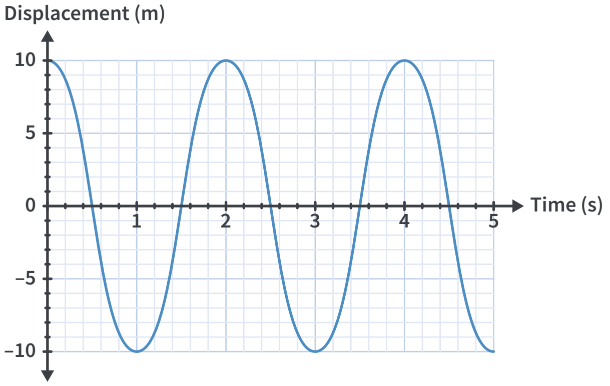
Section B

6 [The Doppler effect is a detected frequency change in a wave due to the relative motion between a wave source and an observer.[1]] [Since the pedestrian and the ambulance are moving towards each other, the pedestrian will hear a greater sound frequency (pitch) when compared to a stationary ambulance.[2]]

- I have used the relevant theory: the Doppler effect.[1]
- I have explicitly addressed the observed sound of the moving ambulance compared with a stationary ambulance.[2]
- I have related my answer to the context of the question.

7 gamma rays, X-rays, green light, red light, infrared waves, microwaves

8 Displacement (m)



- I have drawn a cosine graph with a period of 2 seconds.
- I have drawn a cosine graph with an amplitude of 10 m.
- I have drawn a cosine graph starting at (0, 10) and finishing at (5, −10).
- I have included an appropriate and consistent scale on the axes.
- I have included axis labels with units.

9 $\Delta s = \text{circumference} = 2\pi r = 2 \times \pi \times 6.37 \times 10^6 = 4.00 \times 10^7$ m

$n = \frac{c}{v}$ $\therefore 1.4 = \frac{3.0 \times 10^8}{v}$ $\therefore v = 2.14 \times 10^8$ m s^{-1} (1 MARK)

$T = \Delta t = \frac{\Delta s}{v} = \frac{4.00 \times 10^7}{2.14 \times 10^8} = 0.187$ s (1 MARK)

$f = \frac{1}{T} = \frac{1}{0.187} = 5.4$ Hz, so it will travel around the Earth 5.4 times per second. (1 MARK)

10 **a** B and D. Some of the red light will be refracted along direction *D* as the prism has a lower refractive index for red light than yellow light, but there will also be a portion of the light which is reflected in direction *B*.

b B. Total internal reflection will occur as the blue light has a greater refractive index than the yellow light.

11 $n_1 \sin(\theta_c) = n_2$ $\therefore 1.43 \times \sin(67.0°) = n_2$

$n_2 = 1.32$ $\therefore n_{cladding} \le 1.32$ (1 MARK)

The cable installer should use fibre OF-SNAGZ. (1 MARK)

12 **a** $\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{5.0 \times 10^{14}} = 6.0 \times 10^{-7}$ m (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(2 - \frac{1}{2}\right) \times 6.0 \times 10^{-7} = 9.0 \times 10^{-7}$ m (1 MARK)

b $p.d. = n\lambda$ $\therefore 9.0 \times 10^{-7} = 2 \times \lambda$ (1 MARK)

$\lambda = 4.5 \times 10^{-7}$ m (1 MARK)

13 Use initial travelling wave to find wave speed on the string:

$v = \frac{\lambda}{T} = \frac{0.080}{0.020} = 4.0$ m s^{-1} (1 MARK)

For a standing wave to form with one fixed end:

$f = \frac{nv}{4L}$ $\therefore 20 = \frac{n \times 4.0}{4 \times 0.50}$ (1 MARK)

This gives $n = 10$ but n must be odd for a string with one fixed end to form a standing wave, so DeAndre cannot form a standing wave with a frequency of 20 Hz. (1 MARK)

14 $v = f\lambda$ $\therefore 340 = 85 \times \lambda$ $\therefore \lambda = 4.0$ m (1 MARK)

For Jess: $p.d. = |S_1J - S_2J| = \sqrt{15^2 + 20^2} - 15 = 10$ m (1 MARK)

$p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 3$ $\therefore$ Destructive interference occurs so Jess does not hear the sound well/at all. (1 MARK)

For Viv: $p.d. = |S_1V - S_2V| = \sqrt{48^2 + 20^2} - 48 = 4$ m (1 MARK)

$p.d. = n\lambda$ where $n = 1$ $\therefore$ Constructive interference occurs so Viv hears the sound well. (1 MARK)

15 **a** $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ $\therefore 1.00 \times \sin(75°) = 1.5 \times \sin(\theta_2)$ (1 MARK)

$\theta_2 = 40°$ (1 MARK)

b The angle of refraction where the light enters the glass is equal to the angle of incidence where the light exits the glass because the surfaces are parallel (i.e. alternate angles or 'Z' angles).

$n_2 \sin(\theta_2) = n_1 \sin(\theta_3)$ $\therefore 1.5 \times \sin(40°) = 1.00 \times \sin(\theta_3)$

$\theta_3 = 75°$

c [The ray exits the bottom layer of glass with an angle of refraction equal to 75°[1]][because when light passes through a medium with parallel boundaries the angle of travel is unchanged which is shown by Snell's law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2) = n_1 \sin(\theta_3)$ $\therefore \theta_1 = \theta_3$.[2]]

- I have explicitly addressed the angle of refraction when exiting the glass.[1]
- I have used the relevant theory: Snell's law.[2]

16 [This statement is correct[1]][because Young's double-slit experiment demonstrates interference[2]][which is strictly a wave property.[3]][The particle model incorrectly predicts just two bright bands on the screen.[4]]

- I have explicitly addressed whether the statement is correct or incorrect.[1]
- I have used the relevant theory: Young's double-slit experiment.[2]
- I have used the relevant theory: interference as a wave property.[3]
- I have used the relevant theory: why the particle model cannot explain the double slit result.[4]

17 $\lambda = \frac{v}{f} = \frac{340}{425} = 0.800$ m (1 MARK)

$p.d. = n\lambda = 3 \times 0.800 = 2.40$ m (1 MARK)

Distance moved from centre is $\frac{p.d.}{2} = 1.20$ m (1 MARK)

18 [The statement is incorrect.[1]][For a travelling wave,[2]][all knots will oscillate with an amplitude of 2.0 cm.[3]][For a standing wave,[4]][only knots which exist at antinodes will oscillate with an amplitude of 2.0 cm and all other points will have smaller oscillations (nodes will not oscillate at all).[5]]

- I have explicitly addressed whether the statement is correct or incorrect.[1]
- I have explicitly addressed travelling waves.[2]
- I have used the relevant theory: travelling waves.[3]
- I have explicitly addressed standing waves.[4]
- I have used the relevant theory: standing waves.[5]

19 **a** [The centre band is a high intensity bright band[1]][because at the centre the path difference is zero,[2]][meaning that constructive interference occurs.[3]]

- I have explicitly addressed the intensity of light in the centre.[1]
- I have used the relevant theory: path difference.[2]
- I have used the relevant theory: how path difference affects wave interference.[3]

b B. The fringe space formula $\left(\Delta x = \frac{\lambda L}{d}\right)$ shows that decreasing the wavelength of light decreases fringe spacing so all bands move closer together.

c For second dark fringe: $p.d. = \left(n - \frac{1}{2}\right)\lambda$

$800 \times 10^{-9} = \left(2 - \frac{1}{2}\right)\lambda$ (1 MARK)

$\lambda = 5.33 \times 10^{-7}$ m (1 MARK)

For first bright band:

$p.d. = n\lambda = 1 \times 5.33 \times 10^{-7} = 5.33 \times 10^{-7}$ m (1 MARK)

11A Experimental design of the photoelectric effect

Theory review questions

1 C

2

Independent variable(s)	Dependent variable(s)	Controlled variable(s)
V2, V6	V1, V3	V4

3 A **4** D **5** D

Exam-style questions

This lesson

6 Convert from electron-volts to joules:
$3.2 \text{ eV} = 3.2 \times 1.6 \times 10^{-19} = 5.1 \times 10^{-19}$ J

7 A. The cut-off potential has the same numerical value as the KE_{max} $\therefore V_0 = 0.2$ V

8 $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times (9.1 \times 10^{-31}) \times (2.2 \times 10^6)^2 = 2.2 \times 10^{-18}$ J (1 MARK)

$KE_{max} = \frac{2.2 \times 10^{-18}}{1.6 \times 10^{-19}} = 14$ eV (1 MARK)

9 **a** [Electrons are ejected with a range of energies.[1]][As the reverse potential is increased, fewer electrons have enough energy to reach the collector and so current decreases.[2]][The current is zero at point X since this is the value of reverse potential corresponding to the stopping voltage.[3]][At this point, the reverse potential prevents even the most energetic electrons from reaching the collector plate and so the current is zero.[4]][The kinetic energy of these electrons, measured in eV, has the same numerical value as the stopping voltage.[5]]

- I have used the relevant theory: electrons with a range of energies.[1]
- I have explicitly addressed why the current decreases as the magnitude of the reverse potential increases.[2]
- I have explicitly addressed why current is zero at X.[3]
- I have used the relevant theory: stopping voltage.[4]
- I have used the relevant theory: stopping voltage as a way of evaluating kinetic energy.[5]

b $KE_{max} = 1.1$ eV (1 MARK)

$KE_{max} = 1.1 \times 1.6 \times 10^{-19} = 1.8 \times 10^{-19}$ J (1 MARK)

10 $KE_{max} = \textit{light energy delivered to each electron} - \phi$

$KE_{max} = 3.70 - 2.90 = 0.80$ eV (1 MARK)

$KE_{max} = 0.80 \times 1.6 \times 10^{-19} = 1.3 \times 10^{-19}$ J (1 MARK)

11 [Ejected electrons will have a range of kinetic energies, with the maximum value of 0.1 eV.[1]][The maximum kinetic energy is the difference between the energy absorbed (2.9 eV) and the work function (2.8 eV).[2]] [Some electrons will be more tightly bound to the metal than others; hence not all electrons will be ejected with the maximum kinetic energy.[3]]

- I have explicitly addressed the kinetic energy of ejected electrons.[1]
- I have used the data provided in my answer.[2]
- I have used the relevant theory: the work function.[3]

12 $\phi = \frac{4.2 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.625$ eV (1 MARK)

$KE_{max} = \textit{light energy delivered to each electron} - \phi$

$KE_{max} = 4.2 - 2.625 = 1.6$ eV (1 MARK)

13 $KE_{max} = 0.6$ eV (1 MARK)

$KE_{max} = \textit{light energy delivered to each electron} - \phi$

$0.6 = 2.8 - \phi$ (1 MARK)

$\phi = 2.2$ eV (1 MARK)

14 $KE_{max} = 6.67$ eV

$KE_{max} = 6.67 \times 1.6 \times 10^{-19} = 1.067 \times 10^{-18}$ J (1 MARK)

$KE_{max} = \textit{light energy delivered to each electron} - \phi$

$1.067 \times 10^{-18} = \textit{light energy delivered to each electron} - 6.93 \times 10^{-19}$ (1 MARK)

$\textit{light energy delivered to each electron} = 1.8 \times 10^{-18}$ J (1 MARK)

Previous lessons

15 3*R* above the surface means 4*R* from the centre. Use the inverse square law.

$g_2 = \frac{g_1}{\left(\frac{r_2}{r_1}\right)^2} = \frac{3.71}{4^2}$ (1 MARK)

$g_2 = 0.232$ N kg^{-1} (1 MARK)

16 $F_g = G\frac{M_1 M_2}{r^2} = G\frac{M^2}{r^2}$ $\therefore 3.40 \times 10^{17} = 6.67 \times 10^{-11} \times \frac{(8.50 \times 10^{22})^2}{r^2}$ (1 MARK)

$r = 1.19 \times 10^9$ m (1 MARK)

17 $v = f\lambda$ $\therefore 340 = 180 \times \lambda$ $\therefore \lambda = 1.89$ m

18 $0.20 \times 10^{-3} = 2.0 \times 10^{-4}$ s

$v = \frac{\Delta d}{\Delta t} = \frac{0.25}{2.0 \times 10^{-4}} = 1250$ m s^{-1} (1 MARK)

$v = f\lambda$ $\therefore 1250 = f \times 9.0$

$f = 1.4 \times 10^2$ Hz (1 MARK)

Key science skills

19 [The work function or the specific metal used must be controlled throughout the experiment to achieve a valid result.[1]][As the metal used has a direct effect on the maximum kinetic energy of photoelectrons it should remain constant as not to interfere with the investigation.[2]]

- I have explicitly stated a controlled variable.[1]
- I have used the relevant theory: photoelectric experiment.[2]

20 Uncertainty $= \frac{1}{2} \times$ smallest gradation on scale $= \frac{1}{2} \times 0.2 = 0.1$ A

11B Changing intensity in the photoelectric effect

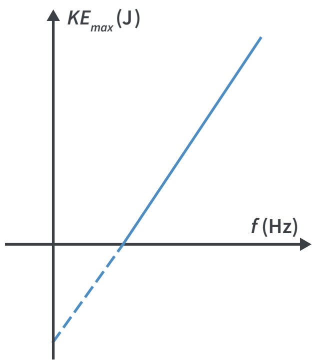
Theory review questions

1 D **2** A **3** D **4** A

Exam-style questions

This lesson

5



[The results are the same as the initial experiment[1]][as changing intensity does not change the kinetic energy of the photoelectrons.[2]]

- I have explicitly addressed the similarity of the graphs.[1]
- I have used the relevant theory: changing intensity of light in the photoelectric experiment.[2]

6 **a** C

b D

7 $KE_{max} = 1.85\ \text{eV} = 1.85 \times 1.6 \times 10^{-19}\ \text{J} = 3.0 \times 10^{-19}\ \text{J}$

Previous lessons

8 [Gen will hear the sound at a higher frequency than if the ambulance was stationary as it approaches,[1]][at the same frequency as if it was stationary when it is directly in front of her,[2]][and then at a lower frequency when it is driving away from her.[3]][These observations are caused by the Doppler effect.[4]]

- I have explicitly addressed the sound as the ambulance approaches.[1]
- I have explicitly addressed the sound as the ambulance is directly in front of Gen.[2]
- I have explicitly addressed the sound as the ambulance drives away.[3]
- I have used the relevant theory: the Doppler effect.[4]

9 **a** $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(400 \times 10^3 + 6.37 \times 10^6)^2}$ (1 MARK)

$g = 8.70\ \text{N kg}^{-1}$ (1 MARK)

b $F = mg = 4.17 \times 10^5 \times 8.70 = 3.63 \times 10^6\ \text{N}$

Key science skills

10 **a** [Voltage is independent because it is deliberately changed by the experimenter.[1]][Photocurrent is dependent because it depends on the selected voltage value.[2]]

- I have used the relevant theory: independent variables.[1]
- I have used the relevant theory: dependent variables.[2]

b Controlled variable (we are told the intensity is kept constant)

c [If the aim of the experiment is to see the impact of changing intensity, the experimenter will directly change the intensity.[1]] [Therefore, the intensity of light is an independent variable.[2]]

- I have used the relevant theory: independent variables.[1]
- I have explicitly addressed the question.[2]

11C Changing frequency in the photoelectric effect

Theory review questions

1 B **2** D **3** C **4** B **5** A

Exam-style questions

This lesson

6 A. $\phi = hf_0 = 4.14 \times 10^{-15} \times 3.6 \times 10^{14} = 1.5\ \text{eV}$

7 [Isabella is correct.[1]][No photocurrent is being measured as the light used is below the threshold frequency of the metal used. To produce a photocurrent the incident light must exceed this threshold frequency, as suggested by Isabella.[2]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: threshold frequency.[2]

8 **a** $KE_{max} = hf - \phi \ \therefore 0.8 = 9.5 \times 10^{14} \times 4.14 \times 10^{-15} - \phi$ (1 MARK)

$\phi = 3.1\ \text{eV}$ (1 MARK)

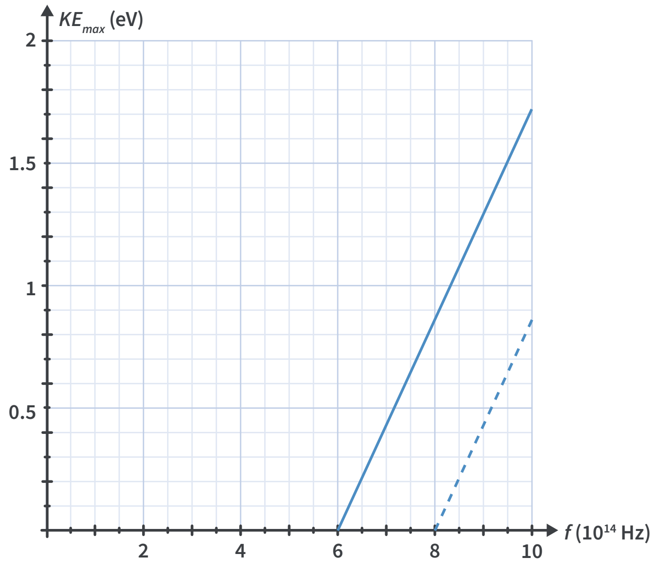
b $\phi = hf_0 \ \therefore 3.1 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 7.6 \times 10^{14}\ \text{Hz}$ (1 MARK)

9 $KE_{max} = h(f - f_0) \ \therefore 2.6 \times 10^{-19} = 6.63 \times 10^{-34} \times (f - 5.5 \times 10^{14})$ (1 MARK)

$f = 9.4 \times 10^{14}\ \text{Hz}$ (1 MARK)

10 When the work function is increased by a factor of one-third, it shifts the vertical axis intercept down by one-third. This is equivalent to shifting the horizontal axis intercept to the right by one-third (from 6×10^{14} Hz to 8×10^{14} Hz).



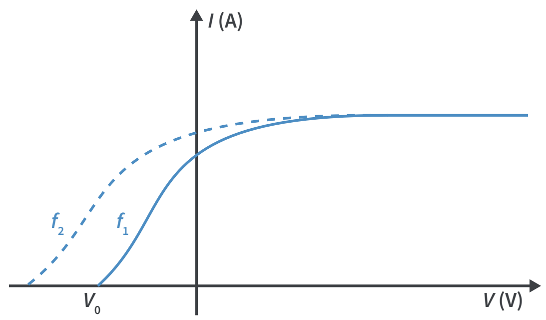
I have drawn the graph parallel to the original.

I have drawn the graph shifted down appropriately.

11 **a** $KE_{max} = hf - hf_0 = h(f - f_0) = 4.14 \times 10^{-15} \times (7.3 \times 10^{14} - 5.8 \times 10^{14})$ (1 MARK)

$KE_{max} = 0.62$ eV $\therefore V_0 = 0.62$ V (1 MARK)

b



12 **a** $c = f\lambda \therefore 3.0 \times 10^8 = f \times 3.75 \times 10^{-9}$

$f = 8.0 \times 10^{14}$ Hz (1 MARK)

$KE_{max} = 1.25$ eV $= 1.25 \times 1.6 \times 10^{-19}$ J $= 2.0 \times 10^{-19}$ J (1 MARK)

$KE_{max} = hf - \phi \therefore 2.0 \times 10^{-19} = 6.63 \times 10^{-34} \times 8.0 \times 10^{14} - \phi$ (1 MARK)

$\phi = 3.3 \times 10^{-19}$ J (1 MARK)

b $\phi = hf_0 \therefore 3.304 \times 10^{-19} = 6.63 \times 10^{-34} \times f_0$ (1 MARK)

$f_0 = 5.0 \times 10^{14}$ Hz (1 MARK)

Previous lessons

13 **a** $g = G\frac{M}{r^2} \therefore 1.62 = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{r^2}$ (1 MARK)

$r = 1.569 \times 10^7$ m (1 MARK)

Distance above Earth's surface:
$1.569 \times 10^7 - 6.37 \times 10^6 = 9.32 \times 10^6$ m (1 MARK)

b [No, he will not feel the same as standing on the Moon[1]][because the normal force, which we feel, is different in each case.[2]][In orbit, $F_N = 0$,[3]][whereas when standing still on the Moon $F_N = F_g = 1.62 \times m$.[4]]

I have explicitly addressed whether Steve will feel the same.[1]

I have used the relevant theory: feeling normal force.[2]

I have used the relevant theory: forces in orbit.[3]

I have used the relevant theory: force in equilibrium.[4]

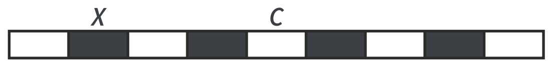
14 **a** [The centre is a bright band[1]][because path difference at this point is zero[2]][and so constructive interference occurs.[3]]

I have explicitly addressed the question.[1]

I have used the relevant theory: path difference.[2]

I have used the relevant theory: constructive interference.[3]

b



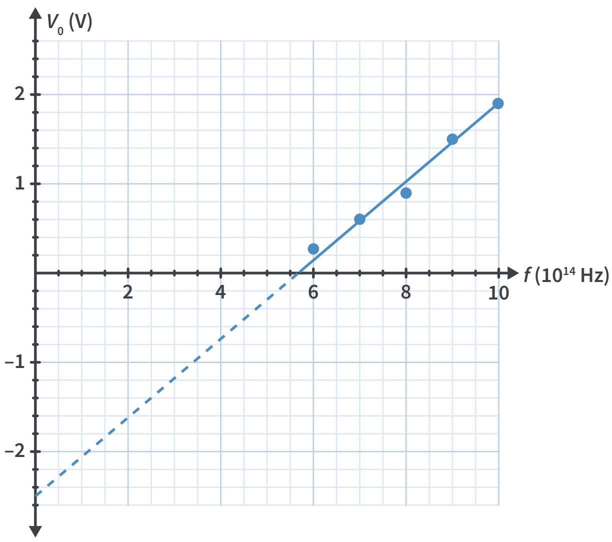
(1 MARK)

$\frac{p.d.}{\lambda} = \frac{8.925 \times 10^{-7}}{595 \times 10^{-9}} = 1.5$ (1 MARK)

So $p.d. = \left(n - \frac{1}{2}\right)\lambda$ where $n = 2$ $\therefore$ associated with second dark band.

Key science skills

15 **a**



I have identified the independent and dependent variables.

I have drawn the horizontal axis as the independent variable, and included correct units.

I have drawn the vertical axis as the dependent variable, and included correct units.

I have included an appropriate and consistent scale on the axes.

I have correctly plotted data point.

- I have drawn an appropriate line of best fit.
- I have used a dashed line for the part of the graph which is below the horizontal axis.

b Independent variable: frequency of incident light (1 MARK)
Dependent variable: stopping voltage (1 MARK)

c Use the horizontal axis intercept on the line of best fit:
$f_0 = 5.7 \times 10^{14}$ Hz.

Any value within 0.25×10^{14} Hz of this value is acceptable.

d Use two points from the line of best fit to calculate the gradient:
$h = \frac{rise}{run} = \frac{1.90-0.60}{10.0\times10^{14}-7.0\times10^{14}}$ (1 MARK)

$h = 4.3 \times 10^{-15}$ eV s. Other values are acceptable as long as gradient is calculated using two points on line of best fit. (1 MARK)

e $\phi = 2.5$ eV (1 MARK)

Use the negative value of the vertical axis intercept on the line of best fit to determine the work function. Any value within 0.1 eV of this value is acceptable.

The metal is europium. (1 MARK)

11D What the photoelectric effect means

Theory review questions

1 B **2** B

3

		Wave	Particle
Energy Distribution	Description	D5	D2
	Prediction	P2	P5
Frequency	Description	D6	D4
	Prediction	P6	P1
Intensity	Description	D3	D1
	Prediction	P3	P4

Exam-style questions

This lesson

4 [Max Planck is correct.[1]][The wave model of light predicts that the maximum kinetic energy of electrons should depend on the intensity of incident light[2]][but kinetic energy is observed to be independent of intensity so the wave model of light cannot fully explain the photoelectric effect.[3]]

- I have explicitly addressed who is correct.[1]
- I have used the relevant theory: wave model prediction (three options possible).[2]
- I have used the relevant theory: actual (corresponding) observation of the photoelectric effect.[3]

5 $E_{photon} = hf = 6.63 \times 10^{-34} \times 4.0 \times 10^{14}$ (1 MARK)

$E_{photon} = 2.7 \times 10^{-19}$ J (1 MARK)

6 [The wave model incorrectly predicts that by increasing the intensity of light enough, electrons would be emitted.[1]][The particle model predicts that increasing intensity (at a given frequency) would increase the number of photons but not their energy.[2]][So, as long as the frequency is below the threshold frequency there is insufficient energy to eject electrons.[3]]

- I have used the relevant theory: wave model prediction.[1]
- I have used the relevant theory: particle interpretation of intensity.[2]
- I have used the relevant theory: threshold frequency.[3]
- I have related my answer to the context of the question.

7 **a** $E_{photon} = hf = 4.14 \times 10^{-15} \times 3.80 \times 10^{15} = 15.7$ eV (1 MARK)

$KE_{after} = KE_{before} - E_{photon} = 160 - 15.7 = 144$ eV (1 MARK)

b $c = f\lambda \ \therefore 3.0 \times 10^{8} = 3.80 \times 10^{15} \times \lambda$

$\lambda = 7.9 \times 10^{-8}$ m = 79 nm

8 [Erwin's result is evidence for the particle-like nature of light[1]][which states that increasing intensity only increases the number of photons, rather than the energy of each photon.[2]][Hence the kinetic energy of ejected electrons does not change.[3]][The result contradicts the wave model of light which states that increasing intensity of light would increase the kinetic energy of photoelectrons.[4]]

- I have explicitly addressed what the result reveals about the nature of light.[1]
- I have used the relevant theory: particle interpretation of intensity.[2]
- I have used the relevant theory: particle model prediction.[3]
- I have used the relevant theory: wave model prediction.[4]
- I have related my answer to the context of the question.

9 $\Delta KE_{electron} = E_{photon} = 15$ eV

$E_{photon} = hf \ \therefore 15 = 4.14 \times 10^{-15} \times f$ (1 MARK)

$f = 3.6 \times 10^{15}$ Hz (1 MARK)

10 [Observation 3 contradicts the wave model of light.[1]][According to the wave model, light is a continuous distribution of energy[2]][which must be absorbed over a period of time until an electron in the plate has enough energy to be emitted.[3]]

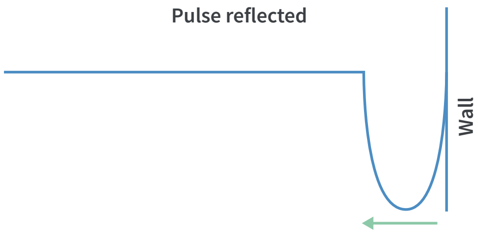
- I have explicitly addressed which observation the wave model fails to predict.[1]
- I have used the relevant theory: wave interpretation of light.[2]
- I have used the relevant theory: wave model prediction.[3]

11 [When the photoelectric experiment is conducted it is observed that there is negligible time delay[1]][and the maximum kinetic energy of an electron is not affected by the intensity alone.[2]][A photon has a discrete amount of energy so the emission of an electron is instant if the electron absorbs a photon with sufficient energy.[3]][As stated by the particle model of light, for a fixed frequency, intensity is a measure of the number of photons per unit time and does not affect individual photons. As an electron's kinetic energy is determined by the absorption of a single photon, it is independent of intensity.[4]]

- I have explicitly addressed an observation that support the particle model of light.[1]
- I have explicitly addressed a second observation that support the particle model of light.[2]
- I have used the relevant theory: evidence for the particle-like nature of light in regards to the first observation.[3]
- I have used the relevant theory: evidence for the particle-like nature of light in regards to the second observation.[4]

Previous lessons

12



13 When the intensity (amplitude) of oscillation significantly increases.

OR

The students observe a standing wave.

14 $mg\Delta h = \frac{1}{2}mv^2$

$m \times 9.8 \times 150 = \frac{1}{2} \times m \times v^2$ (1 MARK)

$v = 54 \text{ m s}^{-1}$ (1 MARK)

Key science skills

15 [The students observe a systematic error.[1]][Systematic error is a consistent and repeated difference between the measured results and the true values of the intended measurements.[2]][It may have occurred as a result of an incorrectly calibrated voltmeter **OR** due to a difference between the surfaces of the zinc plates which would mean they have different work functions.[3]]

- I have explicitly addressed the type of error.[1]
- I have used the relevant theory: systematic error.[2]
- I have explicitly addressed why a systematic error could have occured.[3]
- I have related my answer to the context of the question.

Chapter 11 Review

Section A

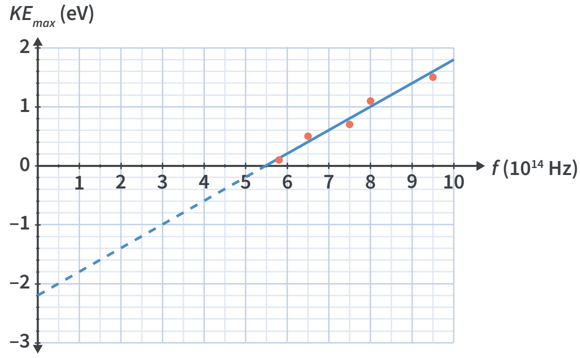
1 A

2 C. Note that the particle model can explain this observation but it does not provide evidence for the particle model because the wave model can explain it too.

3 D 4 D 5 C

Section B

6 a



- I have identified the independent and dependent variables.
- I have drawn the horizontal axis as the independent variable, and included correct units.
- I have drawn the vertical axis as the dependent variable, and included correct units.
- I have included an appropriate and consistent scale on the axes.
- I have correctly plotted the data points.
- I have drawn an appropriate line of best fit.
- I have used a dashed line for the part of the graph which is below the horizontal axis.

b Use the vertical axis intercept on the line of best fit: $\phi = 2.2$ eV. Any value within 0.2 eV of this value is acceptable as long as it corresponds to intercept on line of best fit.

c Use two points from the line of best fit to calculate the gradient:

$h = \frac{rise}{run} = \frac{1.0 - 0.0}{8.0 \times 10^{14} - 5.5 \times 10^{14}}$ (1 MARK)

$h = 4.0 \times 10^{-15}$ eV s. Other values are acceptable as long as the gradient is calculated using two points on the line of best fit. (1 MARK)

d $KE_{electron} = \frac{6.56 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.1 \text{ eV}$ (1 MARK)

$KE_{electron} = E_{photon} - \phi \therefore 4.1 = E_{photon} - 1.8$

$E_{photon} = 5.9 \text{ eV}$ (1 MARK)

7 a $KE_{max} = 1.4$ eV and $\phi = \dfrac{7.36 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.6$ eV

$KE_{max} = E_{photon} - \phi \;\therefore 1.4 = E_{photon} - 4.6$ (1 MARK)

$E_{photon} = 6.0$ eV (1 MARK)

Aragorn is incorrect. (1 MARK)

b [Tauriel's observations provide evidence for a particle model rather than a wave model as they indicate the existence of a threshold frequency.[1]][The wave model predicts that increasing intensity also increases the energy delivered to each electron and that the energy is absorbed over time, so any frequency should be able to eject photoelectrons.[2]][The particle model predicts that increasing intensity increases the number of photons but not their energy, so it will not increase the energy absorbed by each electron.[3]][Tauriel's observations are consistent with the particle model rather than the wave model because increasing both intensity and time did not result in electrons being ejected.[4]]

- I have explicitly addressed the reason the observations support a particle model over a wave model.[1]
- I have used the relevant theory: the wave model predictions.[2]
- I have used the relevant theory: the particle model predictions.[3]
- I have explicitly addressed Tauriel's observations and the models.[4]

8 a [When reverse potential is zero, the photocurrent will be largest as photoelectrons of most kinetic energies will arrive at the collector anode.[1]][As Aliya increases the reverse potential, it will repel photoelectrons of increasing kinetic energy so the number of photoelectrons arriving at the anode will decrease.[2]][This will occur until the reverse potential is high enough to repel the most energetic photoelectrons and the photocurrent is zero. This is called the stopping voltage.[3]]

- I have explicitly addressed the photocurrent at no reverse potential.[1]
- I have explicitly addressed the photocurrent as the reverse potential increases.[2]
- I have used the relevant theory: stopping voltage.[3]

b $KE_{max} = 5.0$ eV (1 MARK)

$KE_{max} = 5.0 \times 1.6 \times 10^{-19} = 8.0 \times 10^{-19}$ J (1 MARK)

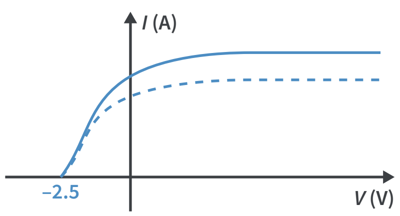
c $\phi = hf_0 \;\therefore 3.0 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 7.2 \times 10^{14}$ Hz (1 MARK)

d $KE_{max} = hf - \phi \;\therefore 5.0 = 4.14 \times 10^{-15} \times f - 3.0$ (1 MARK)

$f = 1.9 \times 10^{15}$ Hz (1 MARK)

9 a



- I have drawn a curve with the same x-intercept.
- I have drawn a curve with a lower y value.
- I have drawn a curve with a similar shape.

b [The fact that both curves share the same horizontal axis intercept (stopping voltage) is evidence for the particle model of light.[1]][This indicates that the maximum kinetic energy of photoelectrons is the same for both intensities.[2]][The particle model correctly predicts that increasing the intensity will increase the number of photons released but not the energy of the photons[3]][and so the kinetic energy of photoelectrons will not change.[4]][The wave model incorrectly predicts that increasing the intensity will deliver more energy to each electron and therefore increase the kinetic energy of the photoelectrons.[5]]

- I have explicitly addressed a feature of the graph that supports the particle model rather than the wave model.[1]
- I have used the relevant theory: stopping voltage as a way to evaluate KE_{max}.[2]
- I have used the relevant theory: particle interpretation of intensity.[3]
- I have used the relevant theory: particle model prediction.[4]
- I have used the relevant theory: wave model prediction.[5]

c [For large positive values of V, all of the available photoelectrons are being collected and increasing V does not change the number of available electrons.[1]][Since there are no more photoelectrons to be collected, increasing the voltage will not result in an increase in photocurrent so the graph is flat.[2]]

- I have used the relevant theory: electrode potential in the photoelectric effect.[1]
- I have explicitly addressed the reason the graph is flat for large values of V.[2]

d $KE_{max} = 2.5 \text{ eV} = 2.5 \times 1.6 \times 10^{-19} \text{ J} = 4.0 \times 10^{-19}$ J (1 MARK)

$KE_{max} = \dfrac{hc}{\lambda} - \phi$

$4.0 \times 10^{-19} = \dfrac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{\lambda} - 1.8 \times 10^{-19}$ (1 MARK)

$\lambda = 3.4 \times 10^{-7}$ m (1 MARK)

10 a [This statement is false.[1]][Electrons are released with a range of kinetic energies because different electrons require different amounts of energy to break free.[2]][The work function describes only the most loosely bound electrons.[3]]

- I have explicitly addressed whether the statement is correct.[1]
- I have used the relevant theory: photoelectron kinetic energy.[2]
- I have used the relevant theory: work function.[3]

b [While the frequency is greater than the threshold frequency, there will be a photocurrent.[1]] [When the frequency is at or below the threshold frequency there will be no photocurrent.[2]]

- I have explicitly addressed the photocurrent when the frequency is greater than the threshold frequency.[1]
- I have explicitly addressed the photocurrent when the frequency is less than or equal to the threshold frequency.[2]

11 **a** $KE_{max} = \frac{1}{2}mv^2 = \frac{1}{2} \times 9.1 \times 10^{-31} \times (1.22 \times 10^6)^2 = 6.77 \times 10^{-19}$ J (1 MARK)

$KE_{max} = \frac{6.77 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.2$ eV $\therefore V_s = 4.2$ V (1 MARK)

b $KE_{max} = hf - \phi \;\therefore 6.77 \times 10^{-19} = 6.63 \times 10^{-34} \times 1.96 \times 10^{15} - \phi$ (1 MARK)

$\phi = 6.2 \times 10^{-19}$ J (1 MARK)

c $\phi = hf_0 \;\therefore 4.33 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 1.046 \times 10^{15}$ Hz (1 MARK)

$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{1.046 \times 10^{15}} = 2.9 \times 10^{-7}$ m (1 MARK)

12A Comparing light and matter

Theory review questions

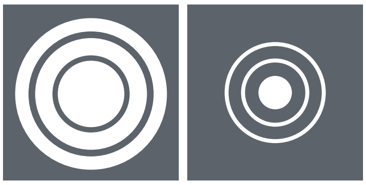
1 D **2** D **3** C **4** D

5 B **6** A

Exam-style questions

This lesson

7 a



Original pattern New pattern

I have drawn concentric circles.

I have drawn concentric circles with a noticeably reduced radius.

b [The pattern will be larger than the original.[1]][The extent of diffraction is inversely proportional to the size of the aperture (diffraction $\propto \frac{1}{w}$) so as it decreases, the pattern will increase in size.[2]]

I have explicitly addressed the change in the pattern's size.[1]

I have used the relevant theory: extent of diffraction.[2]

8 $\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{1.67 \times 10^{-27} \times 2.85 \times 10^{8}}$ (1 MARK)

$\lambda = 1.39 \times 10^{-15}$ m (1 MARK)

9 $E = \frac{hc}{\lambda}$ $\therefore$ $1.20 \times 10^{4} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{\lambda}$ (1 MARK)

$\lambda = 1.04 \times 10^{-10}$ m

Since the diffraction patterns are the same, the wavelength of the electron must be equal to the wavelength of the X-ray. $\lambda_e = 1.04 \times 10^{-10}$ m (1 MARK)

10 a $E = 50 \times 10^{3} \times 1.6 \times 10^{-19} = 8.0 \times 10^{-15}$ J (1 MARK)

$p = \frac{E}{c}$ $\therefore p = \frac{8.0 \times 10^{-15}}{3.0 \times 10^{8}} = 2.7 \times 10^{-23}$ kg m s^{-1} (1 MARK)

b $p = mv$, $KE = \frac{1}{2}mv^2$ $\therefore$ $KE = \frac{p^2}{2m} = \frac{(2.7 \times 10^{-23})^2}{2 \times 9.1 \times 10^{-31}}$ (1 MARK)

$KE = 4.0 \times 10^{-16}$ J (1 MARK)

c [The patterns would be similar.[1]][The momentum is equal, so the de Broglie wavelength of the electron and the wavelength of the photon is equal. As the extent of diffraction depends on the wavelength, this leads to similar diffraction patterns.[2]]

I have explicitly addressed the similarity of the patterns.[1]

I have used the relevant theory: comparing the diffraction of light and matter.[2]

11 $\lambda = \frac{h}{p_e}$ $\therefore$ $0.20 \times 10^{-9} = \frac{6.63 \times 10^{-34}}{p_e}$

$p_e = p_x = 3.32 \times 10^{-24}$ kg m s^{-1} (1 MARK)

$E = p_x c$ $\therefore E = 3.32 \times 10^{-24} \times 3.0 \times 10^{8} = 9.95 \times 10^{-16}$ J

$E = 6.2 \times 10^{3}$ eV (1 MARK)

12 [When an electron is fired through the double slits, it creates a single spot on the screen which indicates discrete[1]][particle-like properties.[2]] [However, over time the spots form an interference pattern[3]][which is a wave property.[4]]

I have used the relevant theory: discreteness of results.[1]

I have explicitly addressed particle behaviour in the double slit experiment.[2]

I have used the relevant theory: interference pattern over time.[3]

I have explicitly addressed wave behaviour in the double slit experiment.[4]

13 $E = p_p c$ $\therefore$ $1.38 \times 10^{-14} = p_p \times 3.0 \times 10^{8}$ (1 MARK)

$p_p = p_e = 4.60 \times 10^{-23}$ kg m s^{-1} (1 MARK)

$p_e = m_e v$ $\therefore$ $4.60 \times 10^{-23} = 9.1 \times 10^{-31} \times v$

$v = 5.1 \times 10^{7}$ m s^{-1} (1 MARK)

14 [Eva's hypothesis is correct[1]][and Sam's hypothesis is incorrect.[2]][For a given aperture size, diffraction depends only on wavelength (diffraction $\propto \frac{\lambda}{w}$) and photons and electrons which have the same energy will not have the same wavelength.[3]]

I have explicitly addressed Eva's hypothesis.[1]

I have explicitly addressed Sam's hypothesis.[2]

I have used the relevant theory: comparing the diffraction of photons and electrons.[3]

Previous lessons

15 $GPE_{top} + KE_{top} = GPE_{bot} + KE_{bot}$ $\therefore mgh_{top} + \frac{1}{2}mv_{top}{}^2 = mgh_{bot} + \frac{1}{2}mv_{bot}{}^2$

$1000 \times 9.8 \times 10 + 0 = 0 + \frac{1}{2} \times 1000 \times v^2$ (1 MARK)

$v = 14$ m s^{-1} (1 MARK)

16 [Ariel experiences more bass as lower frequencies have a longer wavelength which diffract more.[1]][She cannot hear the high pitches until she approaches the door as high pitches diffract less due to their shorter wavelengths.[2]][This occurs because diffraction is directly proportional to the wavelength of the incident wave to the aperture.[3]]

I have explicitly addressed why Ariel hears the low frequency sounds from further away.[1]

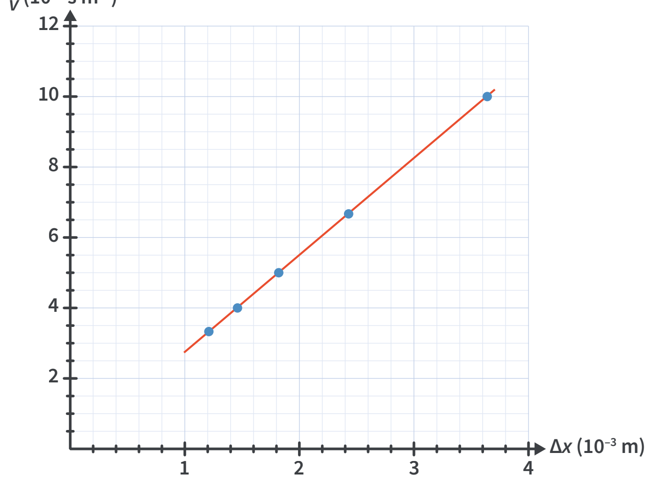
I have explicitly addressed why Ariel hears the higher frequencies only when she is close.[2]

I have used the relevant theory: diffraction.[3]

I have related my answer to the context of the question.

Key science skills

17



I have plotted Δx on the horizontal axis against $\frac{1}{v}$ on the vertical axis with correct units.

I have included a consistent and appropriate scale on the axes so that data takes up at least half the space on each axis.

I have plotted all data values.

I have drawn a line of best fit.

12B Heisenberg's uncertainty principle

Theory review questions

1 A **2** B **3** C **4** D

Exam-style questions

This lesson

5 D

6 D. As the electron is going through a circular hole rather than a slit, its x- and y-position uncertainties decrease. This corresponds with an increase in the uncertainty of the momentum in both the x- and y-directions.

7 [The diffraction pattern of electrons when passing through a single slit[1]] [can be explained by Heisenberg's uncertainty principle[2]] [as a decrease in position uncertainty due to the slit, which increases momentum uncertainty.[3]] [After many electrons have traveled through, this range of possible momenta creates a diffraction pattern.[4]]

I have explicitly addressed the single slit experiment.[1]

I have explicitly addressed Heisenberg's uncertainty principle.[2]

I have used the relevant theory: Heisenberg's uncertainty principle.[3]

I have explicitly addressed the diffraction pattern.[4]

8 a [Classical laws cannot account for the wave properties of matter[1]] [which are significant only at small scales.[2]] [The de Broglie wavelength of large objects is negligible so we do not need to consider their wave properties.[3]] [For small objects, however, the de Broglie wavelength is large enough that they demonstrate significant wave properties.[4]]

I have explicitly addressed the wave properties of matter.[1]

I have explicitly addressed the reason classical laws are not appropriate at small scales.[2]

I have used the relevant theory: de Broglie wavelength at large scales.[3]

I have used the relevant theory: de Broglie wavelength at small scales.[4]

b [Classical laws assume it is possible to have unlimited certainty in the measurements of physical quantities but this assumption is not appropriate at small scales.[1]] [Heisenberg's uncertainty principle puts a limit on the certainty of measurements.[2]] [At large scales the uncertainty is insignificant compared to the size and momentum of the objects.[3]] [At small scales the uncertainty is significant compared to the small size and momentum of the objects.[4]]

I have explicitly addressed the reason classical laws are not appropriate at small scales.[1]

I have explicitly addressed Heisenberg's uncertainty principle.[2]

I have used the relevant theory: Heisenberg's uncertainty principle at large scales.[3]

I have used the relevant theory: Heisenberg's uncertainty principle at small scales.[4]

9 [Alice is correct[1]] [and Tadhg is incorrect.[2]] [According to Heisenberg's uncertainty principle, there is significant uncertainty at the scale of electrons. Classical physics, which relies upon certainty to make predictions, is not appropriate at such small scales.[3]]

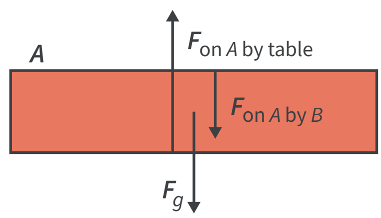
I have explicitly addressed Alice's claim.[1]

I have explicitly addressed Tadhg's claim.[2]

I have used the relevant theory: Classical laws fail.[3]

Previous lessons

10 a



I have drawn two arrows to represent the contact forces originating from the contact surfaces.

I have drawn an arrow to represent the force due to gravity originating from the centre of mass.

- I have drawn all arrows in the correct direction.
- I have labelled the arrows.
- I have drawn the arrows with appropriate size: the vector sum of the downwards forces must equal the upwards force.

b [0 N.[1]][There is no normal force as the block is accelerating at the same rate as the blocks around it.[2]]

- I have explicitly addressed the force on block *B* by block *A*.[1]
- I have used the relevant theory: normal force on objects in freefall.[2]

11 a $v = \frac{\Delta s}{\Delta t}$ $\therefore 3.0 \times 10^8 = \frac{d}{8 \times 60 + 19}$ (1MARK)

$d = 1.50 \times 10^{11}$ m (1MARK)

b Microwaves, visible light, ultraviolet, X-rays, gamma rays.

Key science skills

12 a The size of the slit **OR** type of particle.

b [The momentum (**OR** speed **OR** energy) is the property which Davisson can change as an independent variable.[1]][This changes the electron's wavelength according to $\lambda = \frac{h}{p}$ which affects the diffraction pattern.[2]]

- I have explicitly addressed a property of electrons.[1]
- I have used the relevant theory: de Broglie wavelength.[2]

12C Absorption and emission spectra

Theory review questions

1 D	**2** D	**3** A	**4** B	**5** D
6 B	**7** C	**8** B	**9** A	

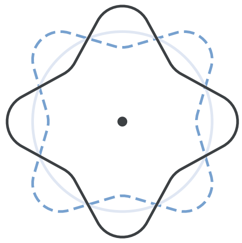
Exam-style questions

This lesson

10 [An electron in a sodium atom exists in discrete energy levels.[1]][Photons are emitted when electrons transition to lower energy levels.[2]][Hence a sodium vapour lamp[3]][will only emit discrete wavelengths of light corresponding to the difference in energy levels.[4]]

- I have used the relevant theory: discrete electron energy levels.[1]
- I have used the relevant theory: energy level transitions.[2]
- I have related my answer to the context of the question.[3]
- I have explicitly addressed the reason wavelengths are discrete.[4]

11 [The wave model of the electron states that an electron has a de Broglie wavelength.[1]][For a stable orbit to exist a standing wave must form, where the circumference of the orbit is an integer multiple of the wavelength $n\lambda = 2\pi r$.[2]][Since only certain discrete electron wavelengths are able to exist and wavelength relates to energy, only discrete energy levels of electrons are allowed to exist.[3]]



- I have explicitly addressed electrons having wave-like properties.[1]
- I have used the relevant theory: electron standing waves.[2]
- I have explicitly addressed the reason energy levels are discrete.[3]
- I have provided a diagram of an electron standing wave around a nucleus in my answer.

12 a $n_4 - n_1 = 3.61$ eV, $n_3 - n_1 = 3.19$ eV (1 MARK)

$n_2 - n_1 = 2.10$ eV, $n_4 - n_3 = 0.42$ eV (1 MARK)

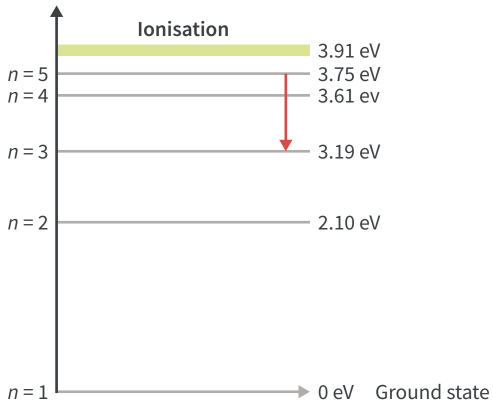
$n_4 - n_2 = 1.51$ eV, $n_3 - n_2 = 1.09$ eV (1 MARK)

b [It is not possible[1]][because there is no difference of 2.3 eV between electron energy levels.[2]]

- I have explicitly addressed whether the observation is possible.[1]
- I have used the relevant theory: discrete energy transitions.[2]

c $\Delta E = hf = 4.14 \times 10^{-15} \times 1.353 \times 10^{14} = 0.560$ eV (1 MARK)

$0.56 = E_5 - E_3$



(1 MARK)

d $E_{photon} = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^8}{14 \times 10^{-9}} = 89$ eV

$\therefore E_{photon} \geq E_{ionisation}$ (89 eV ≥ 3.91 eV)

$KE_{electron} = E_{photon} - E_{ionisation} = 89 - 3.91 = 85$ eV

[The electron would be emitted from the atom (ionisation)[1]] [because the electron energy will be greater than the ionisation energy.[2]] [The electron will have a final kinetic energy of 85 eV.[3]]

- I have explicitly addressed what would happen to the electron.[1]
- I have used the relevant theory: ionisation energy.[2]
- I have explicitly addressed the final energy of the electron.[3]
- I have used calculations to support my answer.

13 [As light passes through the exosphere, the elements in the exosphere will absorb certain wavelengths of the light, producing an absorption spectrum.[1]] [By comparing the absorption spectrum frequencies of the exosphere with mercury's unique spectrum, Stephen Hawking can tell if there is mercury present.[2]]

- I have used the relevant theory: absorption spectra production.[1]
- I have explicitly addressed how Stephen Hawking can test for the presence of mercury.[2]
- I have related my answer to the context of the question.

Previous lessons

14 a $F = G\frac{M_1M_2}{r^2} = 6.67 \times 10^{-11} \times \frac{1590 \times 1.90 \times 10^{27}}{(8.10 \times 10^9)^2}$ (1 MARK)

$F = 3.07$ N (1 MARK)

b $g = a \;\therefore G\frac{M}{r^2} = \frac{v^2}{r}$ (1 MARK)

$6.67 \times 10^{-11} \times \frac{1.90 \times 10^{27}}{(75\,600 \times 10^3)^2} = \frac{v^2}{75\,600 \times 10^3}$ (1 MARK)

$v = 4.09 \times 10^4$ m s^{-1} (1 MARK)

15 a [Total internal reflection would not occur.[1]] [When light goes from a lower to a higher refractive index, it will refract towards the normal of the boundary and hence total internal reflection cannot occur.[2]]

- I have explicitly addressed whether total internal reflection will occur.[1]
- I have used the relevant theory: refraction.[2]

b $n_1\sin(\theta_c) = n_2 \;\therefore 1.20 \times \sin(90° - 30°) = n_2$ (1 MARK)

$n_2 = 1.04$ (1 MARK)

Key science skills

16 a [Precision is a measure of the spread of recorded values.[1]] [Jane's results have a range of 7 nm, whilst Al's results range over 14 nm.[2]] [Therefore Jane's results are more precise.[3]]

- I have used the relevant theory: precision.[1]
- I have used 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]] [Jane's average measurement was 2 nm above the true value whilst Al's average was 1 nm below the true value.[2]] [Therefore Al's measurements are more accurate.[3]]

- I have used the relevant theory: accuracy.[1]
- I have used the provided data in my answer.[2]
- I have explicitly addressed which results are more accurate.[3]

12D Production of light

Theory review questions

1 A **2** A **3** C **4** D

Exam-style questions

This lesson

5 B **6** A **7** D **8** A **9** B

Previous lessons

10 a $4\pi^2 r^3 = GMT^2$ (1 MARK)

$4 \times \pi^2 \times (6.37 \times 10^6 + 5.40 \times 10^5)^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times T^2$ (1 MARK)

$T = 5.71 \times 10^3$ s (1 MARK)

b $v = \frac{2\pi r}{T} = \frac{2 \times \pi \times (6.37 \times 10^6 + 5.40 \times 10^5)}{5.71 \times 10^3}$ (1 MARK)

$v = 7.60 \times 10^3$ m s^{-1} (1 MARK)

11 $n_1\sin(\theta_1) = n_2\sin(\theta_2) \;\therefore 1.20 \times \sin(47°) = 1.33 \times \sin(\theta_2)$ (1 MARK)

$\theta_2 = 41°$ (1 MARK)

12 a Measuring device uncertainty is equal to half of the smallest increment shown on the measuring device.

b ± 0.5 lux

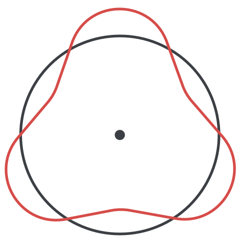
Chapter 12 Review

Section A

1 A **2** D **3** A **4** C **5** B

Section B

6

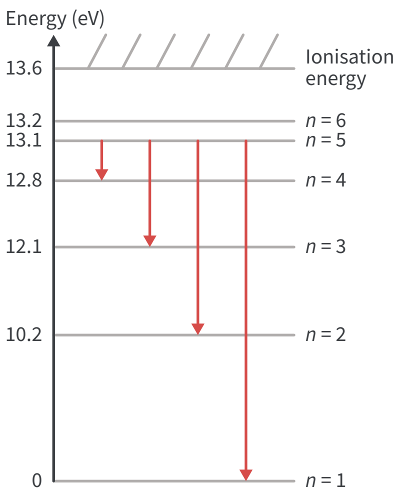


- I have drawn a circle representing the Bohr radius.
- I have drawn a standing wave around the nucleus.
- I have drawn three peaks and three troughs on the standing wave.

7 [Hermione is (unsurprisingly) correct.[1]][Electrons exist in stable orbits only when they can form a standing wave.[2]][This is possible only if the circumference of the orbit is an integer multiple of the wavelength ($n\lambda = 2\pi r$).[3]][Hence only certain wavelengths are allowed and so atomic electrons must exist in discrete energy levels.[4]]

- I have explicitly addressed who is correct.[1]
- I have explicitly addressed wave properties of electrons.[2]
- I have used the relevant theory: electron standing waves.[3]
- I have used the relevant theory: discrete energy levels.[4]

8 a



- I have drawn arrows which start at $n = 5$ and which point downwards.
- I have drawn arrows which end at each level below $n = 5$.

b Lowest frequency means smallest energy difference and photon emission means electron transitions to a lower energy level:

$\Delta E_n = 13.1 - 12.8 = 0.3$ eV

$\Delta E_n = hf \therefore 0.3 = 4.14 \times 10^{-15} \times f$ (1 MARK)

$f = 7 \times 10^{13}$ Hz (1 MARK)

c Longest wavelength means smallest energy difference and photon absorption means electron transitions to a higher energy level:

$\Delta E_n = 12.8 - 12.1 = 0.7$ eV

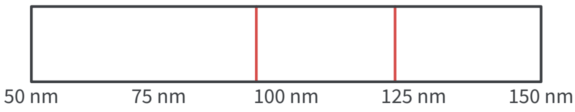
$\Delta E_n = \frac{hc}{\lambda} \therefore 0.7 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^8}{\lambda}$ (1 MARK)

$\lambda = 2 \times 10^{-6}$ m (1 MARK)

d $\Delta E_n = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^8}{\lambda}$

$n_6 - n_1 = 13.2 - 0 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^8}{\lambda} \therefore \lambda = 94$ nm (1 MARK)

$n_2 - n_1 = 10.2 - 0 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^8}{\lambda} \therefore \lambda = 122$ nm (1 MARK)



(1 MARK)

e [The electron must have a de Broglie wavelength[1]][such that the circumference of the orbit is an integer multiple of the wavelength ($n\lambda = 2\pi r$) to occupy a stable orbit.[2]][This allows the electron to act as a standing wave and interfere constructively with itself.[3]]

- I have explicitly addressed the wave behaviour of electrons.[1]
- I have explicitly addressed the conditions for a stable orbit.[2]
- I have used the relevant theory: electron standing waves.[3]

9 a [Alessandro is correct.[1]][Heisenberg's uncertainty principle applies to all scales.[2]][However, the uncertainty is negligible for large objects which is why classical laws of physics are appropriate at large scales.[3]]

- I have explicitly addressed whether Isabella or Alessandro is correct.[1]
- I have explicitly addressed Heisenberg's uncertainty principle.[2]
- I have used the relevant theory: why classical laws apply at large scales.[3]

b [As electrons travel through the slit, the uncertainty in their position decreases.[1]][This results in an increase in the uncertainty in momentum due to[2]][Heisenberg's uncertainty principle.[3]][This appears as a diffraction pattern on the screen behind the slit.[4]]

- I have used the relevant theory: position uncertainty in single slit experiment.[1]
- I have used the relevant theory: momentum uncertainty in single slit experiment.[2]
- I have explicitly addressed Heisenberg's uncertainty principle.[3]
- I have explicitly addressed the electron diffraction pattern.[4]

10 a [The results demonstrate the dual wave-particle nature of matter[1]][since diffraction is a property of waves.[2]]

- I have explicitly addressed what the results reveal about the nature of matter.[1]
- I have used the relevant theory: diffraction as a wave property.[2]

b Same diffraction patterns means same wavelength for electrons and X-rays. (1 MARK)

For the X-rays: $\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{6.0 \times 10^{16}}$ (1 MARK)

$\therefore \lambda_{electron} = 5.0$ nm (1 MARK)

c $p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{5.0 \times 10^{-9}}$ (1 MARK)

$p = 1.33 \times 10^{-25} = 1.3 \times 10^{-25}$ kg m s^{-1} (1 MARK)

d $\lambda = \frac{h}{p} = \frac{h}{mv}$ $\therefore 5.0 \times 10^{-9} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times v}$

$v = 1.46 \times 10^{5}$ m s^{-1} (1 MARK)

$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 9.1 \times 10^{-31} \times (1.46 \times 10^5)^2$ (1 MARK)

$KE = 9.7 \times 10^{-21}$ J (1 MARK)

OR

$KE = \frac{p^2}{2m}$ (1 MARK)

$KE = \frac{(1.33 \times 10^{-25})^2}{2 \times 9.1 \times 10^{-31}}$ (1 MARK)

$KE = 9.7 \times 10^{-21}$ J (1 MARK)

11 [The statement in the article is incorrect[1]][because electromagnetic radiation can also be produced by accelerating charges.[2]][Lasers and LEDs are examples of light being produced by atomic-energy-level transitions. Incandescent globes and synchrotrons are examples of light being produced by accelerating charges.[3]]

- I have explicitly addressed whether the statement is correct.[1]
- I have used the relevant theory: production of light.[2]
- I have explicitly addressed each of the four ways of producing light.[3]

12 [A sodium vapour lamp relies on photon emission from excited atoms to produce light.[1]][Atoms in the gas are energised to reach an excited energy state[2]][and then the energy is emitted in the form of photons as the electrons return to the ground state.[3]]

- I have explicitly addressed how sodium vapour lamps produce light.[1]
- I have used the relevant theory: excited energy states.[2]
- I have used the relevant theory: electron transitions and photon emission.[3]

13 [The screen detects discrete spots which supports the particle model[1]][because the spots represent quantised amounts of light energy (photons) rather than a continuous stream of energy.[2]][Over time, the discrete spots collectively form an interference pattern which cannot be explained by the particle model of light.[3]][A particle model of light would predict that the discrete spots should all land in one of two regions, corresponding to the two slits.[4]]

- I have explicitly addressed a result that supports the particle model of light.[1]
- I have used the relevant theory: the particle-like nature of light.[2]
- I have explicitly addressed a result that does not support the particle model of light.[3]
- I have used the relevant theory: the particle-like nature of light.[4]

Unit 4, AOS 2 Review

Section A

1 D **2** B **3** D **4** C

5 A. At the frequency used, the stopping voltage is smaller for E1. The maximum kinetic energy of electrons is therefore less in E1. This is possible if the threshold frequency is greater, as shown by $KE_{max} = h(f - f_0)$.

Section B

6 **a** $KE = 1.3 \times 1.6 \times 10^{-19} = 2.08 \times 10^{-19}$ J

$KE = \frac{p^2}{2m}$ $\therefore 2.08 \times 10^{-19} = \frac{p^2}{2 \times 9.1 \times 10^{-31}}$ (1 MARK)

$p = 6.15 \times 10^{-25}$ kg m s^{-1} (1 MARK)

$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{6.15 \times 10^{-25}} = 1.1 \times 10^{-9}$ m (1 MARK)

b When diffraction patterns are the same, we can conclude that the momentum of the photon is the same as that of the electron. (1 MARK)

$p_{ph} = p_e = mv = 9.1 \times 10^{-31} \times 7.92 \times 10^{6}$

$p_{ph} = 7.2 \times 10^{-24}$ kg m s^{-1} (1 MARK)

7 [The wave model incorrectly predicts that light energy is continuous and that an electron would absorb the energy over time until it has sufficient energy to be emitted.[1]][The negligible time delay between light being incident on a metal surface and the emission of electrons provides evidence against this prediction.[2]][The wave model also incorrectly predicts that any frequency of light should be able to cause photoelectron emission.[3]][The existence of a threshold frequency provides evidence against this wave model prediction.[4]]

- I have explained one incorrect wave model prediction.[1]
- I have identified the evidence against the wave model regarding the first cited prediction.[2]
- I have explained a second incorrect wave model prediction.[3]
- I have identified the evidence against the wave model regarding the second cited prediction.[4]

An explanation of the wave model's incorrect prediction that maximum electron kinetic energy depends on light intensity would also be a correct response for one of the two discussion points.

8 $V_s = 1.72$ V $\therefore KE_{max} = 1.72$ eV (1 MARK)

$KE_{max} = hf - \phi$ $\therefore 1.72 = 4.14 \times 10^{-15} \times 1.14 \times 10^{15} - \phi$ (1 MARK)

$\phi = 3.00$ eV $\therefore$ The metal is calcium. (1 MARK)

9 Each electron produces a single discrete spot on the screen rather than a continuous interference pattern.

10 **a** $E_{ph} = \Delta E = 13.2 - 10.2 = 3.0$ eV (1 MARK)

$E_{ph} = 3.0 \times 1.6 \times 10^{-19}$ (1 MARK)

$E_{ph} = 4.8 \times 10^{-19}$ J

b $p = \sqrt{2m \times KE} = \sqrt{2 \times 9.1 \times 10^{-31} \times 4.8 \times 10^{-19}}$ (1 MARK)

$p = 9.3 \times 10^{-25}$ kg m s^{-1} (1 MARK)

c 0.3 eV, 0.7 eV, 1.0 eV (1 MARK EACH)

d [For an electron to exist in an atom, a standing wave must form such that the circumference of the orbit is an integer multiple of the wavelength $n\lambda = 2\pi r$.[1]] [Since only certain discrete electron wavelengths are able to exist and wavelength relates to energy, only discrete energy levels of electrons are allowed to exist.[2]]

- I have used the relevant theory: electron standing waves.[1]
- I have explicitly addressed the reason energy levels are discrete.[2]

11 [The light from synchrotrons and incandescent lights are both produced by the acceleration of charged particles.[1]] [Synchrotrons use electric fields to increase the speed of charges and magnetic fields to change their direction, whereas the acceleration of charges for an incandescent light is a result of thermal vibrations.[2]]

- I have explicitly addressed the similarity between synchrotron and incandescent light production.[1]
- I have explicitly addressed the difference between synchrotron and incandescent light production.[2]

12 $\phi = hf_0 \ \therefore 4.33 = 4.14 \times 10^{-15} \times f_0$

$f_0 = 1.05 \times 10^{15}$ Hz (1 MARK)

$f_0 > f_{photon}$ $\therefore$ Photoelectrons will not be released. (1 MARK)

13 [The extent of diffraction is proportional to wavelength, so the diffraction pattern will have a larger spread for larger values of λ.[1]] [For an electron, $\lambda = \frac{h}{mv}$,[2]] [so the diffraction patterns could spread to point *A* if the speed is decreased sufficiently.[3]]

- I have used the relevant theory: the relationship between wavelength and diffraction.[1]
- I have used the relevant theory: the relationship between wavelength and momentum.[2]
- I have explicitly addressed the change in speed that could cause greater diffraction.[3]

14 $gradient = h = \frac{rise}{run} = \frac{1.7 - 0}{(4.0 - 0) \times 10^{14}}$ (1 MARK)

$h = 4.25 \times 10^{-15}$ eV s (1 MARK)

$h = 4.25 \times 10^{-15} \times 1.6 \times 10^{-19} = 6.8 \times 10^{-34}$ J s (1 MARK)

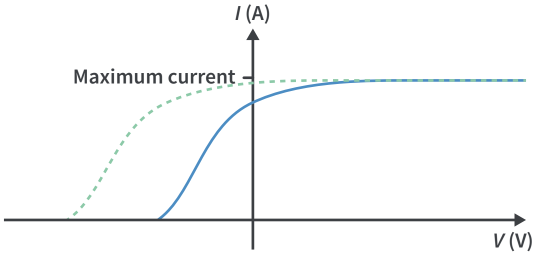
15 [Dorothy may predict this because she knows that increasing the intensity of light means that more energy is delivered by the light.[1]] [However, Dorothy's prediction is incorrect because the energy received by each electron depends on the energy of each photon,[2]] [which is not affected by the intensity of the light.[3]]

- I have used the relevant theory: intensity of light increases energy.[1]
- I have used the relevant theory: energy absorbed by electrons and the particle model of light.[2]
- I have used the relevant theory: independence of electron KE from light intensity.[3]

16 **a** *A* represents the stopping voltage. (1 MARK)

B represents the maximum photocurrent. (1 MARK)

b



- I have drawn the graph with the same maximum current.
- I have drawn the graph with a greater stopping voltage (a more negative horizontal intercept).

17 $\lambda_X = \frac{c}{f} = \frac{3.0 \times 10^8}{5.0 \times 10^{18}} = 6.0 \times 10^{-11}$ m (1 MARK)

The wavelength of electrons and X-rays must be the same: $\lambda_e = \lambda_X$ (1 MARK)

$p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{6.0 \times 10^{-11}} = 1.11 \times 10^{-23}$ kg m s^{-1} (1 MARK)

$KE = \frac{p^2}{2m} = \frac{(1.11 \times 10^{-23})^2}{2 \times 9.1 \times 10^{-31}} = 6.71 \times 10^{-17}$ J (1 MARK)

$KE = \frac{6.71 \times 10^{-17}}{1.6 \times 10^{-19}} = 4.2 \times 10^2$ eV (1 MARK)

A

absorption spectrum the specific set of frequencies of light that a material absorbs due to electron energy transitions p. 415

AC (alternating current) electricity electricity with a periodically alternating direction of current and voltage p. 253, 275

acceleration the rate of change of velocity per unit time (vector quantity) p. 44

accuracy a relative indicator of how well a measurement agrees with the 'true' value of a measurement p. 13

air resistance the force of air particles resisting the motion of objects through the air. Also known as the drag force in air p. 85

alternator a device that transforms kinetic energy into AC electricity by electromagnetic induction; an AC generator p. 253

amplitude the magnitude of the maximum variation of any quantity with a changing value p. 253

angle of incidence (waves) the angle to the normal of a ray approaching a medium boundary p. 350

angle of reflection (waves) the angle to the normal of a ray reflected by a medium boundary p. 350

angle of refraction (waves) the angle to the normal of a ray refracted by a medium boundary p. 350

antinode a point where constructive interference consistently occurs p. 320

aperture a hole, gap, or slit through which a wave travels p. 337

B

bar magnet a permanent magnet in the shape of a prism p. 204

C

centripetal force the net force causing circular motion which is always directed towards the centre of a body's circular path p. 67

charge a quantifiable property which relates to how strongly an object is affected by an electric field p. 197

coherence a property of two wave sources when they create waves of the same frequency in the same medium p. 320

coherent light a beam of light with a consistent frequency and phase p. 421

collision the coming together of two or more objects where each object exerts a force on the other p. 98

compression (longitudinal wave) a point in the medium of a longitudinal wave where pressure is a maximum p. 302

compression (spring) the process of decreasing an object's length p. 122

compression wave see longitudinal wave p. 302

conical pendulum a mass on the end of a string which undergoes horizontal circular motion p. 73

connected bodies two or more objects either in direct contact or attached by a string, rope, or cable p. 58

contracted length (special relativity) the length of an object measured in a reference frame where the object is moving; this length is always shorter than the proper length p. 147

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

conventional current current that is assumed to consist of flowing positive charges so that the direction of current is the direction a positive charge would move p. 211

crest (transverse waves) a point in the medium of a transverse wave where particles have maximum positive displacement p. 302

critical angle (waves) the angle above which total internal reflection occurs p. 350

current (electric) the rate of flow of electric charge p. 268

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. 22

D

DC (direct current) electricity electricity with a constant direction of current and voltage p. 221, 253

de Broglie wavelength the wavelength associated with a particle due to its momentum p. 404

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

design speed the speed on a banked track for which there is no sideways frictional force acting on the vehicle p. 73

diffraction the spread of a wave around an obstacle or through an aperture p. 337

dilated time the time interval between two events measured in a reference frame where the two events occur at different points in space; this time is always greater than the proper time between the events p. 147

dipole a source (field lines point away) and a sink (field lines point towards) paired together p. 170

discrete limited to certain values (not continuous) p. 393, 415

dispersion the separation of white light into its constituent colours due to the different refractive indices for different frequencies (colours) of light in a given medium

displacement the change in position of an object (vector quantity) p. 44

distance the total length of a given path between two points (scalar quantity) p. 44

Doppler effect the detected frequency change due to the relative motion between a wave source and detector p. 315

E

elastic collision a collision in which kinetic energy is conserved p. 112

electric field strength a measure of the electric force that acts per unit of charge at a point in space p. 197

electromagnet a magnet created by an electric current p. 204

electromagnetic induction the production of an electromotive force (EMF) due to the change in magnetic flux through a conducting loop p. 238

electromagnetic spectrum the range of all electromagnetic waves ordered by frequency and wavelength p. 346

electromagnetic wave a transverse wave comprised of changing electric fields and perpendicular changing magnetic fields produced by the acceleration of charged particles. Unlike a mechanical wave, it does not require a medium. p. 346

electromotive force (EMF) the voltage created or supplied due to energy being transformed into electrical potential energy p. 238

electron-volt a measure of energy equal to 1.6×10^{-19} J, derived from the loss or gain of energy by an electron moving across a potential difference of 1 volt p. 376

emission spectrum the specific set of frequencies of light that a material emits due to electron energy transitions p. 415

energy a scalar quantity describing the ability to cause a physical change p. 104

energy dissipation the transfer of energy out of a system p. 112

equilibrium the state of having all the forces acting on an object in balance which means the net force on the object is zero p. 50

equilibrium position (spring-mass system) the position of the mass at which the net force on the mass is zero. This position is always halfway between the two extreme points (endpoints) in oscillatory motion p. 129

error the difference between a measured value and its ‘true’ value p. 13

event something that occurs at a particular location and time p. 147

extension the process of increasing an object’s length p. 122

F

field (model for non-contact forces) a region of space in which each point is subject to a non-contact force p. 170

force a push or a pull with an associated magnitude and direction (vector quantity) p. 50

forced oscillation the oscillation caused by the periodic application of an external driving force p. 327

frame of reference a set of coordinates by which we measure the relative location and motion of objects p. 140

frequency the number of cycles completed per unit of time p. 67, 253, 302

friction a force that resists the relative motion of two surfaces which are in contact p. 58

fringe spacing the distance between adjacent bright or dark bands in a double slit interference pattern p. 361

fundamental frequency the lowest frequency of a standing wave in a given medium p. 331

fusion see nuclear fusion p. 156

G

generator a device that transforms kinetic energy into (either AC or DC) electricity by electromagnetic induction p. 253

gradient the graphical representation of the rate of change of one variable with respect to another p. 30

gravitational field strength a measure of the gravitational force that acts on each unit of mass at a point in space p. 170

gravitational force the force experienced by an object due to the gravitational field of another object p. 50

gravitational potential energy the stored energy associated with the position of an object in a gravitational field p. 117

H

harmonic a standing wave with a frequency equal to an integer multiple of the fundamental frequency p. 331

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. 122

impulse a vector quantity equal to the change in momentum of a body as the result of a force acting over a time p. 98

inclined plane a flat surface that is at an angle to the horizontal plane p. 58

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

induced current the current produced in a conductor due to a changing magnetic field p. 247

inelastic collision a collision in which kinetic energy is not conserved p. 112

inertial frame of reference a non-accelerating frame of reference p. 140

interference superposition creating a larger (constructive) or smaller (destructive) resultant wave p. 320

isolated system a collection of interacting objects for which there is no change in the total mass and energy p. 98

K

kinetic energy the energy of an object due to its motion p. 104

L

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. 22

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. 22

load (electrical) a part of an electrical circuit which consumes power p. 283

longitudinal wave a wave in which the oscillations are parallel to the direction of wave travel and energy transmission p. 302

M

magnetic field a vector field that arises from the movement of charge p. 204

magnetic flux a measure of the amount of magnetic field lines passing through an area p. 238

magnetic flux density the amount of magnetic flux per unit area. Equivalent to magnetic field strength p. 238

magnitude the size or numerical value of a quantity without sign (positive or negative) or direction p. 8

mass-energy equivalence the principle that mass can be considered as a form of energy; mass can be converted into energy and energy can be converted into mass p. 156

mechanical wave a wave which requires a material medium p. 302

medium (waves) the physical substance through which a wave propagates p. 302

model (scientific) a representation of a physical process that cannot be directly experienced p. 2

momentum a vector quantity for a body in motion which is equal to the mass of the body multiplied by its velocity p. 98

monochromatic light light of a single frequency p. 421

monopole a source (field lines point away) or a sink (field lines point towards) of a field in isolation p. 171

N

natural frequency the frequency of oscillations within an object when not driven by an external periodic force p. 327

natural length (spring) the length of a spring when no external forces are acting on it p. 122

net force the vector sum of all forces acting on an object p. 50

Newton's first law law that states an object will accelerate only if a non-zero net force (unbalanced force) acts upon it p. 50

Newton's law of universal gravitation law that states that every object with mass attracts every other object with mass by a gravitational force that increases with the product of their masses and decreases with the square of the distance between the objects p. 171

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. 50

Newton's third law law that states that for every force there is a reaction force in the opposite direction of equal magnitude p. 50

node a point where destructive interference consistently occurs p. 320

non-uniform field a field for which the direction and/or magnitude is different at different locations in space p. 171

normal (waves) an imaginary line perpendicular to the medium boundary at the point of incidence p. 350

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. 50

nuclear fusion two nuclei combine to form a different nucleus, releasing energy in the process p. 156

O

observation the acquisition of data using senses such as seeing and hearing or with scientific instruments p. 2

orbit a circular or elliptical path that an object takes around another p. 184

oscillate move repetitively around a fixed position p. 129

P

particle a theoretical object that is discrete and has a defined location p. 393

path difference the difference in length between paths from two different wave sources to the same endpoint p. 320

period the time taken to complete one cycle p. 67, 253, 302

permanent magnet an object with material properties that cause it to produce a magnetic field p. 204

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

photocurrent the electrical current produced by photoelectrons in the photoelectric effect p. 376

photoelectrons electrons emitted in the photoelectric effect p. 376

photon a particle of light with a discrete amount of energy p. 393

Planck's constant a constant equal to 6.63×10^{-34} J s or 4.14×10^{-15} eV s p. 386

plane a flat, two-dimensional space p. 357

polarised wave a transverse wave whose oscillations exist in only one plane p. 357

polarising filter a material which polarises light passing through it in the direction of the filter's transmission axis p. 357

potential difference see voltage p. 268

power the rate of change in energy with respect to time p. 104

precision a relative indicator of how closely different measurements of the same quantity agree with each other p. 13

projectile an object that has been launched or dropped but does not experience a propulsion/thrust force during its motion p. 85

proper length the length of an object measured in a reference frame where the object is at rest p. 147

proper time the time interval between two events measured in a reference frame where the two events occur at the same point in space p. 147

Q

qualitative data data that cannot be described a numerical values p. 3

quantised see discrete p. 415

quantitative data data that can be described by numerical values p. 3

R

random error the unpredictable variations in the measurement of quantities p. 13

range the maximum horizontal distance a projectile travels p. 85

rarefaction a point in the medium of a longitudinal wave where pressure is a minimum p. 302

refraction the change in direction of a wave moving between two media with different refractive indices p. 350

refractive index for a given medium, the ratio of the speed of light in a vacuum to the speed of light in that medium p. 350

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

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

resistance (electrical) a measure of the opposition to the flow of electric current p. 268

resistor an electrical component that resists the flow of electric current and causes a drop in voltage. Components such as light bulbs and heaters can be modelled as resistors p. 268

resonance the process by which the amplitude of an oscillation increases when forced oscillations match the natural frequency p. 327

resonant frequency see natural frequency p. 327

rest energy the energy of an object at rest, equivalent to the energy of its mass p. 156

rest length see proper length p. 147

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. 275

S

satellite any object that gravitationally orbits another body, such as a planet or star p. 184

scalar quantity a quantity that has only magnitude (size) p. 44

series circuit an electric circuit where components are connected one after the other so that there is only one path along which charge can flow p. 268

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 the digits in a measurement that are confidently known p. 8

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil p. 221, 253

solenoid an electromagnet made from coils of wire p. 204

speed the rate of change of distance per unit time (scalar quantity) p. 44

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation p. 221, 253

spring constant a value that describes the stiffness of a spring p. 122

spring-mass system the combination of a spring and a mass that is attached to one end of the spring p. 129

standing wave a wave for which the positions of maximum amplitude (antinodes) and zero amplitude (nodes) are constant; a superposition of two waves travelling in opposite directions with the same frequency and amplitude p. 331

static field a field that is not changing over time p. 204

stationary wave see standing wave p. 331

stopping voltage the reverse potential that repels the most energetic electrons from the collector electrode and causes the photocurrent to become zero. It has the same numerical value as the maximum kinetic energy of emitted electrons in electron-volts. p. 376

strain potential energy the energy stored by the deformation of an object; also known as elastic potential energy or spring potential energy p. 122

superposition the addition of overlapping waves in the same medium p. 320

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. 13

T

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. 58

theory (scientific) an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation p. 3

threshold frequency the minimum frequency of light at which electrons are ejected from a metal surface in the photoelectric effect p. 386

total internal reflection the reflection of all incident light at a boundary between two media p. 350

total mass energy the sum of the kinetic and rest energy of a mass p. 156

transformer a device that uses electromagnetic induction to transfer power from one electrical circuit to another, commonly with an exchange of current for voltage, or vice versa, while (ideally) keeping the power constant p. 275

transmission (waves) the transfer of wave energy from one wave medium to another wave medium p. 350

transverse wave a wave in which the oscillations are perpendicular to the direction of wave travel and energy transmission p. 302

travelling wave a wave for which the crests and troughs (or compressions and rarefactions) travel in the direction of wave propagation p. 331

trendline see line of best fit or curve of best fit p. 22

trough (transverse waves) a point in the medium of a transverse wave where particles have maximum negative displacement p. 302

U

uncertainty a quantitative indicator of a range that the ‘true’ value of a measurement should lie within p. 14

uniform field a field for which both the direction and magnitude are constant throughout the region of space p. 171

V

validity the qualitative appraisal of how well an experiment measures what it is intended to measure p. 14

vector quantity a quantity that has magnitude (size) and direction p. 44

velocity the rate of change of displacement per unit time (vector quantity) p. 44

voltage a measure of the change in the stored electrical energy per unit charge associated with the difference between two positions in an electric field p. 268

W

wave the transmission of energy via oscillations from one location to another without the net transfer of matter p. 302

wave cycle the process of a wave completing one full oscillation, ending up in a final configuration identical to the initial configuration p. 302

wave speed the speed at which a wave propagates. This is not the speed that particles disturbed by a wave move p. 310

wave-particle duality the concept of light and matter exhibiting both wave behaviours and particle behaviours depending on the context p. 404

wavelength the distance between two identical points in a wave p. 302

work the change in energy caused by a force acting on an object in a direction parallel to its motion p. 104

work function the minimum energy of light required to release the most loosely bound electron from a metal surface p. 376

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Images

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VCAA FORMULA SHEET

Physics formulas provided in the VCE examination.

Motion and related energy transformations

velocity; acceleration	$v = \frac{\Delta s}{\Delta t}; \quad a = \frac{\Delta v}{\Delta t}$
equations for constant acceleration	$v = u + at$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(v + u)t$
Newton's second law	$\Sigma F = ma$
circular motion	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
Hooke's law	$F = -k\Delta x$
elastic potential energy	$\frac{1}{2}k(\Delta x)^2$
gravitational potential energy near the surface of Earth	$mg\Delta h$
kinetic energy	$\frac{1}{2}mv^2$
Newton's law of universal gravitation	$F = G\frac{M_1 M_2}{r^2}$
gravitational field	$g = G\frac{M}{r^2}$
impulse	$F\Delta t$
momentum	mv
Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
time dilation	$t = t_0\gamma$
length contraction	$L = \frac{L_0}{\gamma}$
rest energy	$E_{rest} = mc^2$
relativistic total energy	$E_{total} = \gamma mc^2$
relativistic kinetic energy	$E_k = (\gamma - 1)mc^2$

Fields and application of field concepts

electric field between charged plates	$E = \frac{V}{d}$
energy transformations of charges in an electric field	$\frac{1}{2}mv^2 = qV$
field of a point charge	$E = \frac{kq}{r^2}$
force on an electric charge	$F = qE$
Coulomb's law	$F = \frac{kq_1q_2}{r^2}$
magnetic force on a moving charge	$F = qvB$
magnetic force on a current carrying conductor	$F = nIlB$
radius of a charged particle in a magnetic field	$r = \frac{mv}{qB}$

Generation and transmission of electricity

voltage; power	$V = RI$; $P = VI = I^2R$
resistors in series	$R_T = R_1 + R_2$
resistors in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$
ideal transformer action	$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$
AC voltage and current	$V_{RMS} = \frac{1}{\sqrt{2}}V_{peak}$ $I_{RMS} = \frac{1}{\sqrt{2}}I_{peak}$
electromagnetic induction	EMF: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$ flux: $\Phi_B = B_{\perp}A$
transmission losses	$V_{drop} = I_{line}R_{line}$ $P_{loss} = I_{line}^2R_{line}$

Wave concepts

wave equation	$v = f\lambda$
constructive interference	path difference = $n\lambda$
destructive interference	path difference = $\left(n - \frac{1}{2}\right)\lambda$
fringe spacing	$\Delta x = \frac{\lambda L}{d}$
Snell's law	$n_1\sin\theta_1 = n_2\sin\theta_2$
refractive index and wave speed	$n_1v_1 = n_2v_2$

The nature of light and matter

photoelectric effect	$E_{k\,max} = hf - \phi$
photon energy	$E = hf$
photon momentum	$p = \frac{h}{\lambda}$
de Broglie wavelength	$\lambda = \frac{h}{p}$

Data

acceleration due to gravity at Earth's surface	$g = 9.8$ m s^{-2}
mass of the electron	$m_e = 9.1 \times 10^{-31}$ kg
magnitude of the charge of the electron	$e = 1.6 \times 10^{-19}$ C
Planck's constant	$h = 6.63 \times 10^{-34}$ J s $h = 4.14 \times 10^{-15}$ eV s
speed of light in a vacuum	$c = 3.0 \times 10^{8}$ m s^{-1}
gravitational constant	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}
mass of Earth	$M_E = 5.98 \times 10^{24}$ kg
radius of Earth	$R_E = 6.37 \times 10^{6}$ m
Coulomb constant	$k = 8.99 \times 10^{9}$ N m^2 C^{-2}

Prefixes/Units

p = pico= 10^{-12}	n = nano = 10^{-9}	μ = micro = 10^{-6}	m = milli = 10^{-3}
k = kilo = 10^{3}	M = mega = 10^{6}	G = giga = 10^{9}	t = tonne = 10^{3} kg

OTHER FORMULAS IN THIS BOOK

1E	gradient of a graph	$gradient = \frac{y_2 - y_1}{x_2 - x_1}$
2B	force due to gravity	$F_g = mg$
2C	force down the slope of an inclined plane	$F_{ds} = mg\sin\theta$
2D	circular speed	$v = \frac{2\pi r}{T}$
2D	centripetal force	$F_{net} = \frac{mv^2}{r}$
2E	normal force on a banked track	$F_N = \sqrt{F_{net}^2 + F_g^2}$
2E	centripetal force around a banked track	$F_{net} = F_N \sin\theta = F_g \tan\theta$
2E	design speed around a banked track	$v = \sqrt{rg\tan\theta}$
2F	speed for zero normal force at the top of a circle	$v = \sqrt{rg}$
2G	horizontal component of velocity	$v_x = v\cos\theta$
2G	vertical component of velocity	$v_y = v\sin\theta$
2G	speed of a projectile	$v^2 = v_x^2 + v_y^2$
3A	conservation of momentum	$p_i = p_f$
3A	impulse	$I = \Delta p = m\Delta v$
3B	work	$W = Fs$
3B	power	$P = \frac{\Delta E}{\Delta t}$
3D	speed of objects changing height	$v = \sqrt{-2g\Delta h + u^2}$
4C	conversion of mass into energy	$\Delta E = \Delta mc^2$
5A	inverse square law	$g_2 = \frac{g_1}{n^2}$
5C	orbital radius, mass and period	$4\pi^2 r^3 = GMT^2$
5C	orbital speed	$v = \sqrt{\frac{GM}{r}}$
6A	work done in an electric field	$W = qV = qEd$
7C	frequency and period	$f = \frac{1}{T}$
8A	electrical power	$P = VI = I^2R = \frac{V^2}{R}$
9B	wave speed	$v = \frac{\lambda}{T}$
9F	harmonics for strings with **two** fixed ends	$\lambda = \frac{2L}{n}, n = 1,2,3\ldots$ $f = \frac{v}{\lambda} = \frac{nv}{2L}, n = 1,2,3\ldots$

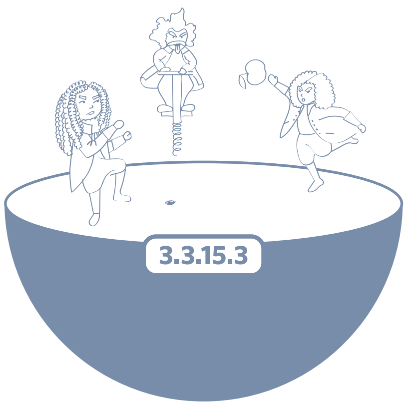
9F	harmonics for strings with **one** fixed end	$\lambda = \frac{4L}{n}$, for odd values of n $f = \frac{nv}{4L}$, for odd values of n
9G	diffraction	$diffraction \propto \frac{\lambda}{w}$
10B	refractive index	$n = \frac{c}{v}$
10B	critical angle	$n_1 \sin\theta_c = n_2$
11C	work function	$\phi = hf_0$
11D	photon energy from wavelength	$E_{photon} = \frac{hc}{\lambda}$
12A	photon energy from momentum	$E_{photon} = pc$
12C	photon energy from electron transition	$E_{photon} = \Delta E$

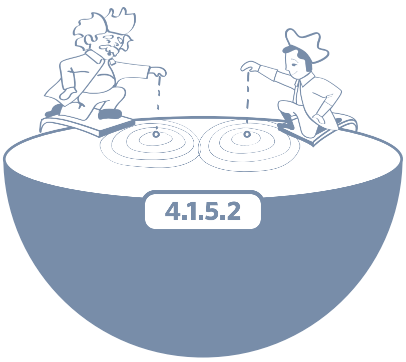
BONUS CHALLENGE: 'JOINING YOUR LEARNING TOGETHER'

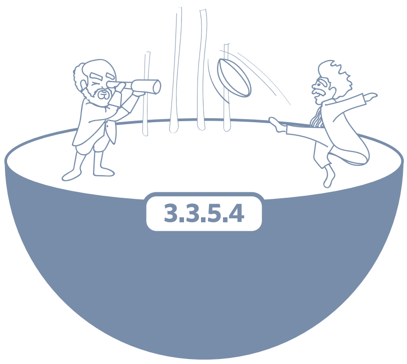
Some of the most difficult concepts from recent VCE exams are represented in the hemispheres below. Writing is a great way to test your knowledge and consolidate your understanding – especially when you're bringing new ideas together! Here's a challenge for you…

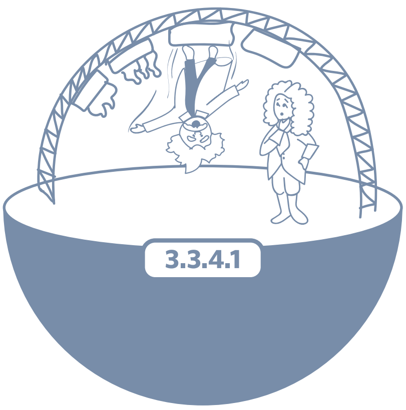
Can you name these famous scientists, identify the Physics concept each of them represents, and join them all together to form a narrative of 200 words or less?

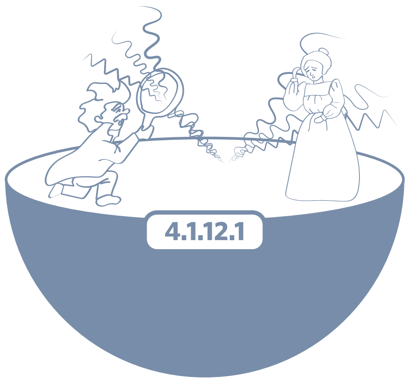
If so, we'd love you to send them through to us at *contentteam@edrolo.com*











Pssst…. The image labelled 3.2.3.1 refers to the concept of electromagnetic induction using an alternator as found in Unit 3, AOS 2, study design dot point 3, key knowledge unit 1 and the Physicist featured alongside Einstein is Caroline Hasslett. Good luck finding the others and joining them together!